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Effect Of Lateral Loading

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ABSTRACT

A description of four tests conducted on longitudinally stiffened plate panels having fixed-end condition at the loaded ends is presented. The specimens were 51 in. wide and consisted of a 1/4 in. plate and four stiffeners. The plate slenderness was $b/t = 60$ and the slenderness of the whole panel was $L/r = 54$. The variable parameter was the intensity of lateral loading ($q = 0$, 6.5, and 13.0 psi). The ultimate axial load varied from 437 kips to 520 kips depending on the magnitude of lateral loading.

The following conclusions can be drawn for the specimen dimensions and loading used in the tests:

a) The strength of the panel is controlled (but not limited) by the buckling strength of the plate. Since stresses in the plate depend on the magnitude of lateral loading, residual stresses, and the end conditions of the panel, the strength of the whole panel also depends on these parameters.

b) In comparison with pinned-end specimens, fixed-end specimens exhibited substantial post-buckling strength, that is, the additional axial strength after the plate has buckled.

1. INTRODUCTION

This report describes a series of tests conducted as part of a research project concerned with the strength of longitudinally stiffened plate panels such as are used in ship bottom plating.

A series of ten tests have been conducted previously (before 1962) on pinned-end panel specimens to investigate the effect of lateral loading, welding residual stresses, and some geometric parameters(1,2)*. A study has been made of the material properties(3) and of the elastic-plastic strength of simply supported rectangular plates subjected to lateral and axial loading(4).

Since the bottom plating of ships of longitudinal construction is continuous over transverse frames, test specimens with loaded ends fixed would approximate its behavior more closely than specimens with simply supported ends.

The present report gives a description of tests on four identical specimens with loaded ends fixed. The variable parameter was the intensity of lateral pressure (0, 6.5 and 13.0 psi). This pressure corresponds to 0, 15, and 30 feet of water head, respectively.

In comparison with the test results of specimens with simply supported ends, the results of the new test series showed that end restraint has considerable influence on the strength of stiffened plate panels.

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* Numbers in parentheses refer to references given in Chapter 10.

The basic data and the ultimate axial loads for these specimens and the specimens described in Reports 248.4[1] and 248.5[2] are listed in Table 1. The discussion of the test results is illustrated with figures and tables. The actual test readings are compiled in a supplementary report, Fritz Engineeering Laboratory Report 248.12A which is available on request.

The magnitude and distribution of residual stresses was found from a short specimen length which was used as a gage portion. In addition to the method of slicing, a simplified non-destructive technique for measuring welding residual stresses in plates was successfully tried out.

2. TEST SPECIMENS

2.1 SPECIMEN PROPORTIONS

The test specimens had the same over-all dimensions as specimens used in pinned-end tests, so that the available apparatus for the application of lateral loading could be employed.

The cross-section of the specimens was identical to that of Type T-7 which is more typical for ship bottom plating than Type T-1. (T-1 and T-7 refer to the specimens described in Reports 248.4[1] and 248.5[2]).

The subpanel width to plate thickness ratio (plate slenderness) was $b/t = 60$ with 1/4 inch plate and 15 inch spacing of the stiffeners. The over-all slenderness of the specimens for the length from one end to the other was $L/r = 54$, where r, the radius of gyration, is based on the subpanel width of the plate rather than on the whole cross section.

The nominal dimensions of the specimens are shown in Fig. 1. Table 3 gives the actual dimensions. Tables 4 and 5 show the initial imperfections in the specimens. The maximum out-of-flatness of the plate was approximately 0.20 in. which was considered fully tolerable.

2.2 FABRICATION OF TEST SPECIMENS

All four specimens were fabricated from two pieces of plate having the same yield strength and from four lengths of rolled beam, 6 Jr. 4.4, of the same heat number. Fig. 2 shows the material cutting diagrams.

The plates were first cut to a 51 in width, and 10 ft. and 11 ft. lengths. The final cutting operations were made by either shearing or sawing in order to avoid residual stresses which would be produced if flame cutting were used. The gage portion for the residual stress measurements was laid out in the middle part of the longer plate between Specimens T-14 and T-15.

The beams, 6 Jr. 4.4, were split along the web by torch to give the required depth of 3 - 5/16 in. of the stiffeners and were cut to the same length as the plates. The effect of cutting by torch was less serious on the web of the stiffener than on the plate, since the stiffeners were later welded to the plate.

Before welding the tee stiffeners to the plates, the plates were cold bent along the stiffener lines in order to compensate for the warpage due to the welding process. During welding the flanges of the stiffeners were heated by torch to produce an initial longitudinal curvature and thus to minimize longitudinal deformations due to welding. An intermittent weld was made first, and then the gaps were filled in.

After one set of readings of gage lengths was taken on the residual stress gage portion, stiffened plates were sawn to the required lengths of the specimens. The top and bottom ends of the specimens were welded to 3/4 in. plates (end plates in Fig. 1) using single-bevel groove joint of full penetration.

The top and bottom of each specimen (outer surfaces of the end plates) were machined plane and parallel to a "smooth finish." The side edges of the specimens were given a "medium finish." Finally, holes for the cap screws which were used to fasten the end plates to the end fixtures were drilled in the end plates.

2.3 MECHANICAL PROPERTIES OF SPECIMEN MATERIAL

The actual mechanical properties of the material were obtained by conducting 13 tension and 6 compression coupon tests. The coupons were made from the reserved pieces of plates and tee stiffeners. In Fig. 2 these pieces are marked with letter C. The coupons for stiffeners were taken from the flange and the web since the material properties of these two parts are often different, the web having a higher yield point than the flange.

The dimensions of the tension coupons were specified according to the ASTM Standards (Designation E8-54T). A gage length of 4 in. was used, and the width of the reduced section was 1 in. The tension coupon tests were conducted on a Tinius Olsen testing machine of 120,000 lb. capacity (the same machine was used for the compression tests). In each test, a load-strain curve was automatically plotted using a Tinius Olsen extensometer Type S-1. Average machine crosshead speed used was 0.02 in./min. before yielding and 0.36 in./min. after yielding.

The compression coupons had a length of 2-3/8 in. and a width of 3/4 in. The compression tests were carried out according to the procedure established in a previous study[3]. A compression jig was used to prevent premature buckling of the coupons. Corrections for nonparallelism of the testing machine head and bed were made by the use of a subpress. The strains were measured by the Huggenberger Extensometers in the elastic range and by the Hubermeter* in the plastic range. The machine crosshead speed used was 0.012 in./min. before yielding and 0.025 in./min. after yielding.

The yield property of the steel was defined by the static yield stress level, σ_{sy}, that is, the yield stress at a zero strain rate.

Results of all the coupon tests are given in Table 2. All of the compression coupons showed a somewhat higher yield stresses than the tension coupons. The compression coupons from the plate had a yield stress about 7.6% higher than the tension coupons, while the flange coupons from the 6 Jr. 4.4 had a yield stress about 7.0% higher. The greatest difference between the tensile and compressive yield stress values was for the web of the 6 Jr. 4.4. The compression coupons showed about 11.6% higher values than the tension coupons. The values obtained for the strain hardening strain in tension and compression do not show any definite relationship.

The strain-hardening modulus had with slight variations a typical value for structural steel of about 100,000 psi (see Table 2).

* See Ref. 5 Rampetsreiter, R. H. "Compressive Properties on Thin Steel Coupons" for the description of this device.

3. TEST SET-UP AND INSTRUMENTATION

3.1 ARRANGEMENT

The test setup consisted of end fixtures, axial and lateral loading systems, and instrumentation. Except for the end fixtures, the setup is the one used in tests on the pinned-end specimens and is described in detail in Report 248.4[1]. Only a brief summary will be given here.

A schematic presentation of the loading system is given in Fig. 3. The axial load was applied to thespecimen through the end fixtures by means of a 5,000,000 lb. Baldwin-Southwark Universal testing machine. Uniform lateral loading was produced by using a pressure box and compressed air. With the specimen as a front wall, the pressure box formed a complete self-balancing enclosure. Lateral forces between the specimen and the pressure box were transmitted through four articulated links at the corners of the specimen.

3.2 END FIXTURES

In order to simulate fixed end condition for the specimen, two sets of end fixtures each composed of an end block and a platen were used as shown in Fig. 4.

The specimen was attached to the end block by bolting the end plate of the specimen to the end block. The connection was made sufficiently strong to develop a full plastic moment in the specimen at the ends.

The end block and the platen were 6 in. wide and all their contact surfaces were flat and parallel to the surfaces of the pedestal and the cross head of the testing machine. The top and bottom platens, 2-1/2 and

3 in. thick, respectively, were needed to provide enough distance between the end block and the testing machine for the connection of the end block to the pressure box. The platen was aligned with the end block by means of four 3/16 in. diameter pintles, the ends of which projected into the holes in the end block and in the platen. See Fig. 4.

The bottom platen extended the full width of the testing machine pedestal (72 in.) and was clamped to the pedestal. The top platen was made of the same width as the specimen (51 in.) in order to attach the end bracing which was used for temporary support of the specimen.

The build-up of the end fixtures required that sufficient axial force be applied to the specimen before lateral loading in order to prevent any rotation of the specimen ends.

3.3 INSTRUMENTATION

Instrumentation for measuring deformation of the specimens consisted of dial and electric resistance strain gages. (The instrumentation for the residual stress measurements is described in Section 6.2).

Dial Gages

All dial gages were AMES dial gages with one thousandth inch divisions and a stroke of one inch. The location of the points at which dial gage readings were made is shown in Fig. 7. The dial gages were used to measure:

1) Lateral deflection of the specimen at a number of points so as to cover, more or less, the whole area of the specimen (Gages 1 through 23 were all C- and E- gages; C = corners, E = end).

2) Rotation of the specimen at the ends. (S - gages; S = slope).

3) Change in the distance between the pedestal and the cross head, longitudinal deflection. (L - gage; L = length).

All dial gages used for lateral deflection measurements were mounted on the dial gage frame as shown in Fig. 5. The dial gage frame was firmly attached to the pedestal of the testing machine. Connection of the dial gages to the specimen was accomplished by means of block wire which was stretched between the gages and small screws on the specimen.

S - gages were used to measure the rotation of the specimen ends during testing. The arrangment for these gages can be seen in Fig. 4 and their location is shown in Fig. 7. At each point, a 3/8-in. diameter round bar was screwed into the end block, and vertical movement was measured at two locations on this bar with dial gages. The difference of dial gage readings divided by the distance between the two measuring points, 9 in., gave the angle of rotation. The effect of the elastic deformation of the end fixtures on the readings was neglected.

Changes in the distance between the ends of the specimen were measured with an L-gage located as shown in Fig. 7. Actually, the variation of the distance from the machine cross head to the pedestal was measured, but this introduced a very small inaccuracy since the deformation of the end fixtures compared with that of the specimen was of a negligible magnitude.

Strain Gages

All strain gages were electric resistance SR-4, Type A-1 linear gages. Location of the gages on the specimen is shown in Fig. 8. At each point two gages were used, one on the front face and the other on the back face of the specimen. Strain readings were made on two strain indicators with switch boxes.

4. TEST PROCEDURE

4.1 PREPARATION

The preparation of the specimens for testing was the same as that used for testing of the pinned-end specimens, and a detailed description of the procedure can be found in F. L. Report 248.4. Only a brief outline of the procedure is given here.

After measuring the specimen dimensions and its initial inperfections, SR-4 gages were cemented and wired. Then the specimen was placed on the machine pedestal and the end plates were bolted to the end blocks. Both front and back faces of the specimen were whitewashed.

For specimens tested under combined axial and lateral loading (T-13 and T-14), the lateral loading system was assembled and the pressure box was attached to the specimen at this stage.

The remainder of the procedure was common to all specimens. The dial gage frame was erected and the dial gages were connected to the specimen. The machine head was aligned to produce as uniform a compression across the specimen as possible. Since the depth of the specimen was very small in comparison to its width, the alignment in direction of depth was difficult and a perfectly uniform pressure was probably not achieved. The maximum load used for the alignment was 150 kips. After the alignment the specimen and the equipment were ready for testing.

4.2 TESTING OF SPECIMENS

A description of the loading sequence and other pertinent operations is given in this section.

At first, the machine head was lowered until it made contact with the top platen and the L and S dial gages were installed. An initial axial force of 50 kips for a lateral pressure of 6.5 psi (1oo kips for 13.0 psi) was applied in order to prevent rotation of the end fixtures which could be caused by applying the lateral load first. The end bracing angles were loosened at a load of about 20 kips.

The lateral pressure was increased from zero to the maximum intensity using increments of 4 psi or less and maintained at the maximum intensity during the further application of the axial load. The axial load was increased in 25 to 100 kip steps. Smaller load increments of 10 to 20 kips were used when the axial load was approaching its estimated maximum value. After reaching the ultimate load a sufficient number of readings were taken to define the nature of the post-ultimate behavior. Then the axial load was reduced stepwise. At a load of about 50 kips, the lateral loading was taken off, the end bracing angles were retightened, and the top S- and L- gages disconnected. After this, the machine cross head was raised.

For testing without lateral loading, the loading operation was correspondingly simplified.

Readings of all gages were taken at each load increment. This was done only after the load became stabilized. Load versus deflection curves were continuously plotted for the longitudinal deflection and the lateral deflection of the stiffeners and plate at the mid-height of the specimen. These curves served as an illustrative indication of the specimen behavior.

The progress of yielding as indicated by the flaking of the white wash observed and recorded.

5. TEST RESULTS

5.1 GENERAL

A general summary of the obtained test results is given in this section. Major properties, ultimate axial load, and the mode of failure are listed for each specimen in Table 1. This table gives information for specimens T1 to T15--all subsequent information is only for the specimens of the current test series, T12 to T15. The photographs of the final yield patterns for the front and back faces of each specimen are shown in Figs. 8 to 15. The longitudinal deflection readings are given in Table 7; they are plotted versus the non-dimensionalized axial load in Fig. 16. The lateral deflection of stiffeners and plate for a half-width of the specimens is plotted versus axial load in Figs. 17 to 20. Figs. 21 to 24 show the complete deformed cross section of mid-height for different loads. The axial strains at these cross sections are given in Figs. 25 to 28 and discussed in Section 5.4. A complete tabulation of all the readings is available in a supplementary report, Fritz Engineering Laboratory Report No. 248.12A.

5.2 DEFORMATION OF SPECIMENS

Lateral and longitudinal deformation of the specimens is described in this section.

Since, in most cases, the specimens deformed symmetrically except at the ultimate loading, only the readings of a small group of lateral deflection gages describing the behavior of a half cross-section at the mid-height are necessary for the qualitative discussion presented here.

The readings of these gages are plotted in Figs. 17 to 20. Neglecting the initial deformation in the plate, the specimen cross section may be considered perfectly straight before the application of loading. Taking this as the original position and correcting the dial gage readings for the horizontal movement of the specimen ends (C gages), the lateral deflections of the dial gage points were plotted.

An inspection of the deflection curves shows that lateral deformation of the panel consisted of two parts: deflection of the stiffeners and the deflection of the plate relative to the stiffeners.* Under the application of lateral loading, deflections of the inner stiffeners were greater than those of the edge stiffeners due to the difference in plate areas supported by them. Conversely, the relative deflection of the plate in the center subpanel was smaller than that in the side subpanels. This difference was caused by the plate in the side subpanels being restrained by the adjacent plate on only one side. The relative deflection of the plate was essentially constant along the center line of a subpanel, except in the areas close to the ends where it gradually reduced to zero.

Application of axial loading in addition to lateral produced only slight, but systematic, changes in the cross section. With the increase of axial loading, the relative deflection of the plate decreased in the center subpanel, while it increased in both side subpanels. The relationship between the change in the relative deflection of the plate and the magnitude of axial loading was approximately linear.

* Hereafter the relative deflection of the plate between the stiffeners will be called simply "relative deflection of the plate."

At a larger magnitude of axial loading (about 375 kips and 340 kips for T13 and T14, respectively), the relative deflection of the plate at mid-height began to increase in the center subpanel and decrease in the side subpanels. Deflection of the plate along the center line of the subpanel also began to deviate from a single long bulge into a regular buckle pattern which developed at the ultimate load. Since the changes in the relative deflections of the plate were very gradual in these loading stages, the commencement of the buckling of the plate could not be pinpointed. However, an estimation of the axial load P_{cr} at which the subpanel would have buckled had it been perfectly flat was made by applying the "δ^2 - method" and was checked by the "top-of-the-knee method." Thus estimated critical axial loads are indicated in Fig. 16.

At the ultimate load the cross section changed more rapidly and suddenly deformed completely. Deformed cross sections at mid-height for various stages of loading, including the consecutive load stages before and after the ultimate load, are shown in Figs. 21 to 24.

Longitudinal deformation is given for all specimens in Fig. 16. As expected the longitudinal distance did not change during the application of increasing lateral pressure.

5.3 STRAINS

Strains in the specimens were measured both in axial and horizontal directions. Readings of horizontal strain gages were taken at the mid-height of the specimens and were used to detect the curvature of the plate. In the plate of the center subpanel the average horizontal tensile strains were less than one tenth of the average axial compressive strains. This indicates that the horizontal expansion of the plate was considerably restrained by the adjacent plates of the side subpanels. Otherwise, horizontal strains equal to the full Poisson ratio effect (about 1/3) would have been detected.

Figs. 25 to 28 show the axial strains in the cross section at mid-height for three consecutive load stages, two before and one after the ultimate load. As seen in the figures, the strain distributions of all the specimens except T12 show similar patterns.

The average axial strains in the plates at the plate buckling loads for T13, T14, and T15 were 865, 890, and 860 micro-inches per inch, respectively. Each of these values does not deviate more than three percent from the average value of 870 which is 81% of the theoretically computed elastic buckling strain. 81% of the theoretical value is essentially the strain that would be predicted considering compressive residual stress in the plate. This clearly indicates that the residual strsses have a direct influence on plate buckling. Lateral loading, on the other hand, was found to have negligible influence on the buckling stress for the specimen dimensions and the loading range used in this test series.

Strain distributions in Fig. 25 through Fig. 28 illustrate the transfer of strains from the plate to the stiffeners near the ultimate load. A comparison of the average axial strains in the plate at the ultimate load for T13, T14 and T15 points out that the average maximum strain in the plate was about the same--970, 990 and 1010 micro-inches per inch for each specimen, respectively, and was essentially equal to the yield strain, 1210 micro-inches per inch, minus the compressive residual strain, 160 micro-inches per inch. This indicates that the ultimate collapse of the panel was caused by the failure of the stiffeners to support the additional axial load created by the transfer of stress from the plate to the stiffeners due to yielding and subsequent unloading of the plate.

5.4 BEHAVIOR OF SPECIMENS DURING TESTING

Since each specimen differed in some way from the others, the behavior of each specimen is discussed separately.

Specimen T12

T12 was tested axially without lateral loading. Since at an early stage of loading, one of the side subpanels yielded due to the eccentricity of loading, the behavior of specimen T12 was considerably different from those described in Sections 5.2 and 5.3.

At a load of 250 kips, yield lines were first noticed on the web of the left edge stiffener at the top and bottom. New yield lines appeared at 300 kips in the plate of the left subpanel near the mid-height and spread over the left subpanel by the time the ultimate load was reached. Between 300 kips and 450 kips (ultimate load), the relative deflection of the plate in the left subpanel increased gradually but kept the shape of a single long bulge along the axial direction, while in the other two subpanels the relative deflection of the plates were practically zero as shown in Fig. 21.

When the ultimate load P_u = 450 kips was reached, plate instability occurred simultaneously in all the subpanels and the cross section deformed rapidly. The average axial strain in the plate of the center and the right subpanels was 854 micro-inches per inch at the ultimate load which is essentially equal to the strains in the other three specimens at plate buckling. The unloading of the plate followed immediately after the plate buckling in the left subpanel, but in the center and the right subpanels where the plate had not yielded, the transfer of the strains from the plate to stiffeners did not take place. This is shown in Fig. 25. Although the specimen eas unable to carry any higher load, it could sustain the present load.

Under the application of an additional axial strain to the specimen, the compressive yield lines developed on the concave side of the buckled plate and the load decreased gradually. After 306 kips, the flanges of the stiffeners buckled locally at the top and bottom;the stiffeners visibly twisted and the load rapidly dropped. This and specimen T15 were the only specimens in which twisting of the stiffeners was observed.

Specimen T13

Specimen T13 was subjected to the combined action of the lateral (q = 6.5 psi) and axial loadings. Due to some initial eccentricity which counteracted the effect of lateral loading, the total lateral deflection of the specimen was relatively small after the lateral loading was full applied. In consequence, the lateral deflection scarcely increased with a increased in the axial load. It became more rapid only after the flanges of the stiffeners started to yield at the bottom.

The first yield lines appeared at the bottom edge of the plate in the side subpanels at P = 50 kips, but they were obviously due to residual stresses caused by the welding of the plate to the end plate. At P = 275 kips some yield lines were observed in the plate near the toes of edge stiffeners. These lines extended with an increase of the axial load. When the load reached 420 kips, the webs and flanges of all the stiffeners were noticed to have yielded at the bottom. After the plate buckled at about 470 kips, short yield lines in the plate at the toes of stiffeners started to cross the subpanels. At the ultimate load, P_u = 495 kips, these yield lines completed the crossing of the breadth of the left and the center sub-panel near the mid-height, and the load dropped suddenly. The final yield pattern is shown in Fig. 7 and 8.

Specimen T14

The lateral loading applied in this test was 13.0 psi. The lateral loading was increased from 0 to its full intensity after the application of an initial axial load of 100 kips. At a lateral load of 10 psi the flanges of the edge stiffeners yielded at the bottom. When the axial load was equal to 250 kips, all the flanges and the webs of the stiffeners had yielded at both loading ends thus creating in essence hinges for any higher axial loads. Further increase of the lateral deflections with an increasing axial load was considerably greater than that in specimen T13. See Figs. 18 and 19.

After plate buckling commenced at about P = 395 kips, the behavior of the specimen, the appearance of the yield lines, and the mode of failure were similar to those of specimen T13. The ultimate load, P_u, was reached at 436 kips.

Specimen T15

Specimen T15 was a duplicate of specimen T12 and thus was subjected only to axial loading. Yield lines due to residual stresses caused by the welding of the plate and the end plates appeared at the loading ends of the plate as early as at P = 300 kips. When the load reached 350 kips, the webs of all the stiffeners were observed to have yielded. The yielding was not confined to any one specific location. At a load of 410 kips short, less than two inches long, yield lines started to appear in the plate along the toes of the stiffeners. They were limited to narrow bands parallel to stiffeners which by the time the load reached 450 kips spread over the full length of the specimen.

At P = 490 kips the right subpanel started to buckle and was immediately followed by the center and the left subpanels. From P = 490 kips till 520 kips short yield lines in the plate were observed to be extending across the subpanels. The specimen failed at P_u = 520 kips when a yield line completely crossed the center subpanel near the mid-height, and the load dropped to 480 kips.

With the application of a small additional straining, and the buckling pattern of the plate became indicated by the suddenly appearing yield lines. This pattern is shown in Figs. 11 and 12.

6. RESIDUAL STRESSES

6.1 INTRODUCTION

Residual stresses influence the strength of stiffened panels considerably as the test results described in Reference 2. Of primary importance are the longitudinal compressive residual stresses in the plate between the stiffeners. Residual stresses in the transverse direction or in the direction of the thickness are small and of minor significance.

In the current tests two different methods of measuring residual stresses were employed on the same gage portion. One was the standard method of sectioning. The other was a non-destructive method which was tried out for the first time in these tests.

Residual stresses were measured in the gage portion between Specimens T13 and T14 marked with the letter R in Fig 2. Since the two groups of specimens, T12-T15 and T13-T14, were fabricated from materials of identical properties and since the same technique was used, it was assumed that residual stresses existing in portion R were representative of the residual stresses in all four test specimens.

The gage points were laid out on both sides of the plate as shown in Fig. 29 and on the stiffeners as shown in Fig. 30.

6.2 INSTRUMENTATION AND PROCEDURE

The instrumentation used in the measurement of residual stresses consisted of a Whittemore gage with a ten-inch gage length and a standard reference bar. Any changes in ambient temperature were taken into account by making three readings on the reference bar after each thirty readings on the specimen.

The holes were drilled at each gage point shown in Figs. 29 and 30 using a special countersink drill bit (No. 57 with the reamer angle of 60^o).

Four sets of readings (Readings A, B, C and D) were needed for the desired residual stress analysis. Initial readings were taken (Readings A), and then the stiffeners were welded to the plate. A second set of readings (Readings B) was made after welding.

The gage portion, marked with letter R in Fig. 2 was then sawn out, and the third set of readings (Reading C) was taken.

The next operation consisted of sawing the gage portion into narrow strips of 1/2 to 1-1/2 inch widths each cut half-way between the gage holes as shown in Fig. 29 (the sectioning operation). 1/2-inch strips were cut in the vicinity of stiffeners where a sharp variation of residual stresses was to be expected. Wider 1-1/2-inch strips were adequate in the plate between the stiffeners because residual stresses varied very little in this area. After sectioning the final measurement was taken on the individual strips (Reading D)

Between individual operations the holes were protected against dirt and mechanical damage by covering them with pieces of masking tape.

The conventional method of measuring residual stresses, the method of sectioning, called for the readings to be taken after the welding and after the sectioning (Readings B and D). Residual stresses were found by subtracting Readings B from Readings D, dividing the difference by Reading B, and computing the residual stresses from the thus obtained strains. Residual stresses computed this way were the final residual stresses due to welding, rolling, and any other causes.

In wide plates as used in stiffened plating residual stresses due to rolling are relatively small, and the final stresses are essentially equal to those produced by welding. When the important stresses are at some distance from the weld, such as in the plate between stiffeners of a stiffened panel, they can be measured by a simplified procedure not requiring sectioning. The method is based on the measurement of elastic strains which are caused by the welding process and is thus not applicable in the areas where inelastic deformations develop due to the effect of heat. In stiffened panels, however, the heat-affected zone is rather narrow relative to the width of the subpanel.

In this method residual stresses are computed from the strains taking place between Readings A and B. This method thus does not require the expensive sectioning and, in fact, can be performed on an actual structure.

6.3 RESIDUAL STRESSES

Residual stress distributions in the plate as computed from the four sets of readings are shown in Fig. 31. The heavy line is based on readings A and B and depicts residual stresses which developed in the process of welding. These stresses were measured without cutting the specimen, that is, using the simplified non-destructive procedure.

The thin line connecting solid dots depicts stresses which were released when the gage section R was cut out. The stresses were obtained from readings B and C and give some indication of the residual stresses in the plate. In fact, the maximum value corresponds to the intensity shown by the other two curves. The distribution, however, is quite different. A similar result was obtained in the measurements conducted in the test series described in Reference 2.

The average weight line with circles gives the residual stresses measured by the method of sectioning. They were computed from readings B and D. These stresses include the stresses due to welding as well as the initial stresses. From a comparison of this curve with the heavy curve which gives the stresses due to welding alone, it is seen that the initial stresses in the plate are relatively small and may be neglected in the analysis.* In the middle subpanel the average compressive stress is 4.8 psi by the method of sectioning and 4.5 ksi by the simplified method. The difference between the two methods being about 6.5 precent is less than the variation of the stress within a subpanel.

Residual stresses in the stiffeners were measured using Readings B and C, and Readings B and D The results for the four stiffeners as shown in Fig. 32 indicate no correlation between the two methods. This is mainly due to the fact that the release of strains depends greatly on the plate being separated or not separated from the stiffener.

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* This conclusion may not be valid for plates of other widths and thicknesses. Nagaraja Rao and Tall, for example, observed initial stresses of considerable magnitude (6 ksi) in 1/2-inch plates of 10 inch width[4].

The simplified method was not attempted on the stiffeners. Initial residual stresses and relatively large heat-affected zones would make this method completely invalid. The only possible application of the method to stiffeners or other small members would be in the quality control of welding (see Sect. 6.4).

It can be thus concluded that the only method to reliably determine residual stresses in the stiffeners is the method of sectioning.

The residual stress plots in Fig. 32 show very little consistency between the individual stiffeners, expecially in the flange. It should, however, be noted that the flange readings were made only on one side since the gage could not be fitted to the bottom side, and no account could be made for the effect of curling, which was quite perceptible after sectioning. Residual stress patterns in the web agree in that each stiffener had a high tensile stress at the toe where the weld was made.

In summary it should be stated that the residual stresses were approximately of the same magntiude and had the same pattern as those measured in pervious tests[(2)]. The residual stress in the plate may be approximated by a uniform pattern with an intensity of about 4./ ksi in compression. The stress at the junction in the plate as well as in the stiffener was tensile approximately equal to the yield point of the material.

6.4. COMMENTS ON NON-DESTRUCTIVE PROCEDURE

It is suggested that the simplified non-destructive method rather than the method of sectioning should be used when only the compressive residual stresses in the plate are to be determined.

Another application of the simplified method would be in the quality control of welding. The measuring holes would be drilled before fabrication. The residual stresses due to welding can serve then as a reliable indicator of whether or not the welder followed a prescribed welding procedure.

When the measuring holes, even being as small as used in tests, are objectionable, little target pieces of metal with predrilled holes can be cemented on the surface and used for the measurements. After completion, these target pieces can be re-used. It is important that the targets be made of a hard metal like stainless steel rather than brass or the like. Otherwise the holes would wear out quite quickly and the readings would become unreliable.

The procedure can be affectively used on any metal: steel, aluminum, etc. In order to be able to compensate for possible changes in the ambient temperature, the reference bar should be made of the same material.

7. SUMMARY

The objective of this group of tests was to investigate the effect of lateral loading on the compressive strength of longitudinally stiffened plate panels having a fixed-end condition at the loaded ends.

Four specimens, T12 to T15, were tested by subjecting them to either axial or combined axial and lateral loading. All of the specimens had identical dimensions, material properties, and residual stress patterns. The end fixtures and other parts of the test setup were designed to furnish a fixed-end condition at the top and bottom ends of the specimen and free edges at the sides. The intensity of lateral loading was the variable parameter (0, 6.5 and 13.0 psi).

With a b/t = 60 the plate in all the specimens buckled before the specimens reached the ultimate load. The axial strain in the plate at buckling was in all cases equal to about 880 microinches per inch which is the theoretically computed elastic buckling strain of a simple supported plate less the strain corresponding to the average compressive residual stress. It may be thus concluded that the buckling strain of the plate was influenced neither by the intensity of lateral loading, nor by the end conditions at the loading edges (aspect ratio of plate subpanels was 3.8). On the other hand, compressive residual stresses in the plate had a direct effect on the buckling strain.

Since the compressive strain in the plate was produced by the combined action of the axial thrust and bending moment, the magnitude of the axial load at the point of plate buckling was influenced by the intensity of lateral loading. This axial load was smaller by 4.1 and 19.4 percent in the specimens subjected to lateral loading of 6.5 and 13.0 psi, respectively, than in the specimen loaded only axially.

Unlike the pinned-end panels[1,2] the fixed-end panels did not reach their ultimate axial load at the point of plate buckling. They exhibited significant post-buckling strength amounting to 5 to 10 percent of the buckling load.

The simplified non-destructive method of measuring welding residual stresses in the stiffened plate was found to be quite reliable and can be recommended for similar cases.

8. ACKNOWLEDGMENTS

This report presents results of four tests conducted on longitudinally stiffened plate panels during 1962 and 1963. This test series is a part of the research program on Built-Up Members in Plastic Design currently being conducted at Fritz Engineering Laboratory, Civil Engineering Department, Lehigh University, Bethlehem, Pennsylvania. Professor William J. Eney is Head of the Laboratory and Dr. Lynn S. Beedle is Director.

The research has been sponsored by the Department of the Navy under the Bureau of Ships Contract NObs 88221 and NObs 90041. The study was initiated by Mr. John Vasta of the Bureau of Ships. His interest in and support of the project are gratefully acknowledged.

The specimens and the modified parts of the testing apparatus were fabricated at Bethlehem Foundry and Machine Company.

The authors wish to express their deep gratitude to Mr. K. R. Harpel with his crew of technicians and to Mr. I. J. Taylor with is Instruments Group for their cooperation and assistance in preparation and execution of the tests. Thankful acknowledgement is also due to numerous research assistants and student helpers who aided during the tests.

Particular thanks must go to Mr. H. L. Davidson for his help in the final preparation of the report. The report was typed with care by Misses M. L. Courtright and R. Fischer and the drawings were done by Messrs. P. Gruner, H. Izquierdo and R. Weiss.

9. TABLES AND FIGURES

TABLE 1: BASIC SPECIMEN DATA (T1 to T15).

Specimen No.	Date Tested	A^* $(in.^2)$	I^* $(in.^4)$	Parameters: $b/_t$	Parameters: $L/_r*$	Parameters: Rotational Restr. By Stiffeners	Parameters: Lateral Ldg. q (psi.)	Parameters: State of Residual Stress	Ultimate Axial Load Test (kips)	Mode of Failure
1	2	3	4	5	6	7	8	9	10	11
T1	2/24/59	17.75	24.41	60	52	Low	0	Rolling & Welding	532	Plate Instability
T2	4/3/59	17.75	24.41	60	52	Low	6.5	Rolling & Welding	450	Plate Instability
T3	4/12/59	17.75	24.41	60	52	Low	13.0	Rolling & Welding	400	Plate Instability
T4	5/14/59	17.75	24.41	60	52	Low	6.5	Rolling & Welding	475	Plate Instability
T5	7/2/59	21.34	29.52	41	52	High (Full Fixity)	6.5	Rolling & Welding	684	Column Instability
T6	6/3/60	16.96	24.54	40	51	Low	6.5	Rolling & Welding	463	Column Instability
T7	7/7/60	15.56	17.58	60	50	Low	0	Rolling & Welding	449	Plate Instability
T8	8/8/60	15.56	17.58	60	50	Low	0	None	493	Plate Instability
T9	8/16/60	15.56	17.58	60	50	Low	0	Welding	422	Plate Instability
T10	1/11/61	15.56	17.58	60	20.7	Low	0	Rolling & Welding	472	Plate Instability

TABLE 1: BASIC SPECIMEN DATA (T1 TO T15) (Cont.)

Specimen No.	Date Tested	A^* ($in.^2$)	I^* ($in.^4$)	b/t	L/r^*	Rotational Restr. By Stiffeners	Lateral Ldg. q (psi)	State of Residual Stress	Ultimate Axial Load Test (kips)	Mode of Failure
				Parameters						
1	2	3	4	5	6	7	8	9	10	11
T11	7/26/60 9/1/60	15.56	17.58	60	50	Low	Used for Residual Stress Measurement			
T12	12/28/62	15.56	17.58	60	53.6	Low	0	Rolling & Welding	450	Plate Instability
T13	3/21/63	15.56	17.58	60	53.6	Low	6.5	Rolling & Welding	495	Plate Instability
T14	4/23/63	15.56	17.58	60	53.6	Low	13.0	Rolling & Welding	436	Plate Instability
T15	6/26/63	15.56	17.58	60	53.6	Low	0	Rolling & Welding	520	Plate Instability

*The areas, moments of inertia, and the L/r ratios are based on the whole cross section of specimen.

Note: Specimens T12 through T15 were tested under the fixed-end condition, while specimens T1 through T10 had pinned ends.

TABLE 2: TENSION COUPON TEST RESULTS (T12 to T15).

Coupons Taken From	Coupon Number	σ_{sy} (ksi)	σ_u (ksi)	Est (10^3 ksi)	Est (in/in)	% Elongation	% Reduction of Area
1	2	3	4	5	6	7	8
	Tension Coupons						
	Pc-19	35.6	60.7	-	-	35.3	44.4
	Pc-20	35.3	61.1	-	0.020	35.9	44.0
	Pc-21	37.1	62.1	0.714	0.021	32.0	46.8
Plate	Pc-22	36.3	61.6	0.616	0.021	32.0	46.2
	Pc-23	35.9	61.4	0.571	0.020	32.7	47.7
	Average	36.0	61.4	0.634	0.021	33.5	45.8
	Compression Coupons						
	AP-16	38.9	-	0.604	0.014	-	-
	AP-17	38.6	-	0.696	0.015	-	-
	Tension Coupons						
	Fc-13	40.0	64.5	0.750	0.022	29.3	39.6
	Fc-14	38.6	64.5	0.692	0.018	30.8	37.7
	Fc-15	41.1	66.8	0.733	0.018	28.3	40.1
Stiffener	Fc-16	34.4*	55.7*	-	0.019	30.6	49.6*
Flange	Average	39.9	65.3	0.725	0.019	29.8	39.1
	Compression Coupons						
	F VIII	42.2	-	0.725	0.018	-	-
	F IX	43.2	-	0.785	0.016	-	-

Table 3. ACTUAL SPECIMEN DIMENSIONS

	Plate			Stiffeners			
Specimen	Width in.	Length in.	Average Thickness in.	Flange Width in.	Flange Thickness in.	Depth in.	Web Thickness in.
1	2	3	4	5	6	7	8
T12	51	57.05	0.265	1.85	0.195	3.31	0.126
T13	51	57	0.267	1.86	0.193	3.32	0.121
T14	51	57	0.265	1.86	0.192	3.31	0.113
T15	51	57.05	0.265	1.87	0.195	3.30	0.116

NOTE: For nominal dimensions, see Fig. 1.

Table 4. INITIAL TILTING AND SPACING OF STIFFENERS

a. Initial Spacing of Stiffeners (in.)

Specimen		e_1	b_1	b_2	b_3	e_2
T12	Top	2.95	15.02	15.02	14.99	3.02
	Bottom	2.97	15.02	15.02	14.99	2.99
T13	Top	3.00	15.02	14.99	15.05	2.95
	Bottom	2.99	15.02	15.00	15.03	2.97
T14	Top	2.99	14.97	14.97	15.00	3.02
	Bottom	2.96	15.00	15.00	15.00	3.02
T15	Top	2.97	15.00	15.03	15.00	3.02
	Bottom	2.97	15.00	15.03	14.97	3.03

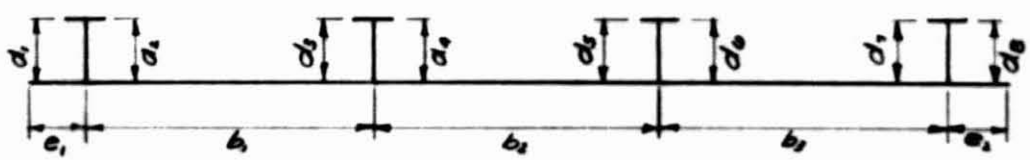


Table 4. INITIAL SPACING AND TILTING OF STIFFENERS (con't)

b. Initial Tilting of Stiffeners (in.)

Specimen		d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8
T12	Top	3.30	3.28	3.29	3.28	3.32	3.29	3.28	3.27
	Bottom	3.27	3.31	3.30	3.30	3.28	3.29	3.28	3.29
T13	Top	3.31	3.30	3.35	3.28	3.26	3.33	3.32	3.32
	Bottom	3.31	3.31	3.31	3.30	3.31	3.30	3.35	3.34
T14	Top	3.26	3.31	3.28	3.28	3.32	3.28	3.28	3.32
	Bottom	3.27	3.32	3.28	3.27	3.31	3.34	3.31	3.32
T15	Top	3.32	3.26	3.36	3.28	3.32	3.31	3.28	3.29
	Bottom	3.32	3.32	3.34	3.32	3.30	3.31	3.36	3.30

Table 5. INITIAL UNFAIRNESS OF PLATES

(10^{-3} in.)

a. Horizontal Sections

Specimen	Section	1	2	3	4	5	6	7
	HT	-18	31	-42	25	30	24	-31
T12	HC	0	57	36	22	60	36	-19
	HB	6	37	21	79	65	20	-12
	HT	43	48	58	58	44	29	30
T13	HC	34	56	30	13	-27	22	3
	HB	33	62	95	98	95	58	22
	HT	66	5	-34	-52	-24	-8	42
T14	HC	30	28	25	12	10	7	5
	HB	97	93	93	49	37	12	14
	HT	-12	17	-1	55	39	-8	-42
T15	HC	-4	41	13	34	-28	39	-38
	HB	5	52	43	42	45	37	-20

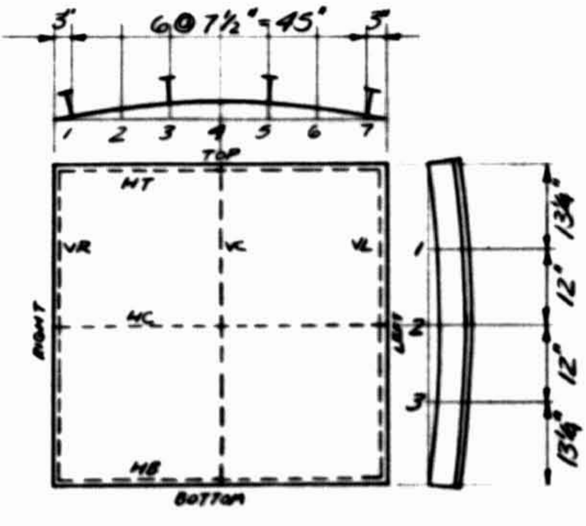
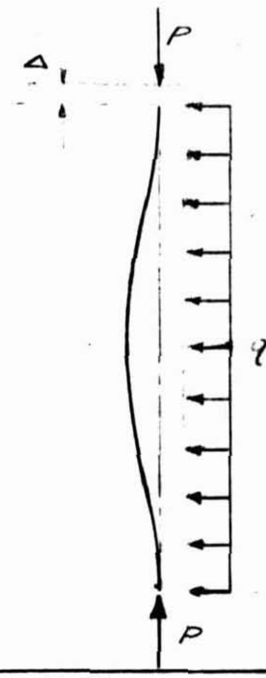


Table 5 (Cont'd)

b. Vertical Sections

Specimen	Section	Points 1	2	3
	VR	13	4	50
T12	VC	6	-1	25
	VL	5	12	-33
	VR	-7	5	78
T13	VC	-11	-47	-14
	VL	-19	9	17
	VR	0	14	18
T-14	VC	-10	-40	-10
	VL	25	17	53
	VR	11	21	27
T-15	VC	7	-2	20
	VL	-16	-3	-48

TABLE 6. LONGITUDINAL DEFLECTIONS



Load No.	T-12 Load P(kips)	T-12 Defl. 10^{-3}in	T-13 Load P(kips)	T-13 Defl. 10^{-3}in	T-14 Load P(kips)	T-14 Defl. 10^{-3}in	T-15 Load P(kips)	T-15 Defl. 10^{-3}in
1	50	0	0	0	0	0	0	0
2	100	15	50	34	50	34	50	7
3	150	16	50	34	100	44	100	31
4	200	35	50	34	100	47	200	45
5	250	46	50	34	100	46	300	61
6	275	50	50	34	100	46	325	64
7	300	56	100	43	100	46	350	67
8	325	60	125	48	100	44	370	70
9	350	65	150	52	150	56	390	74
10	375	70	175	57	200	65	400	75

Table 6: **LONGITUDINAL DEFLECTIONS** (Cont'd)

Load No.	T-12 Load P(kips)	T-12 Defl. 10^{-3}in	T-13 Load P(kips)	T-13 Defl. 10^{-3}in	T-14 Load P(kips)	T-14 Defl. 10^{-3}in	T-15 Load P(kips)	T-15 Defl. 10^{-3}in
11	400	77	175	57	250	76	410	76
12	425	82	225	65	300	84	420	78
13	440	92	275	73	325	89	430	80
14	440	118	325	79	300	87	440	81
15	428	137	350	83	325	89	450	83
16	398	166	375	88	350	94	460	84
17	370	221	400	93	360	97	470	85
18	321	357	420	98	370	100	480	86
19	312	396	440	102	380	103	490	89
20	306	552	450	105	390	104	500	91
21	252	773	460	108	400	108	510	96
22	180	1142	470	112	410	113	480	103
23	---	---	485	118	420	119	470	114
24	---	---	462	125	430	126	454	124
25	---	---	440	134	390	136	434	134
26	---	---	409	148	380	144	420	144
27	---	---	394	156	366	154	400	144
28	---	---	373	169	355	163	350	138
29	---	---	150	136	336	175	300	130
30	---	---	150	131	320	173	200	114

Table 6: **LONGITUDINAL DEFLECTIONS** (Cont'd)

Load No.	T-12 Load P(kips)	T-12 Defl. 10^{-3}in	T-13 Load P(kips)	T-13 Defl. 10^{-3}in	T-14 Load P(kips)	T-14 Defl. 10^{-3}in	T-15 Load P(kips)	T-15 Defl. 10^{-3}in
31	---	---	---	---	300	169	---	---
32	---	---	---	---	280	166	---	---
33	---	---	---	---	260	162	---	---
34	---	---	---	---	100	132	---	---
35	---	---	---	---	100	132	---	---

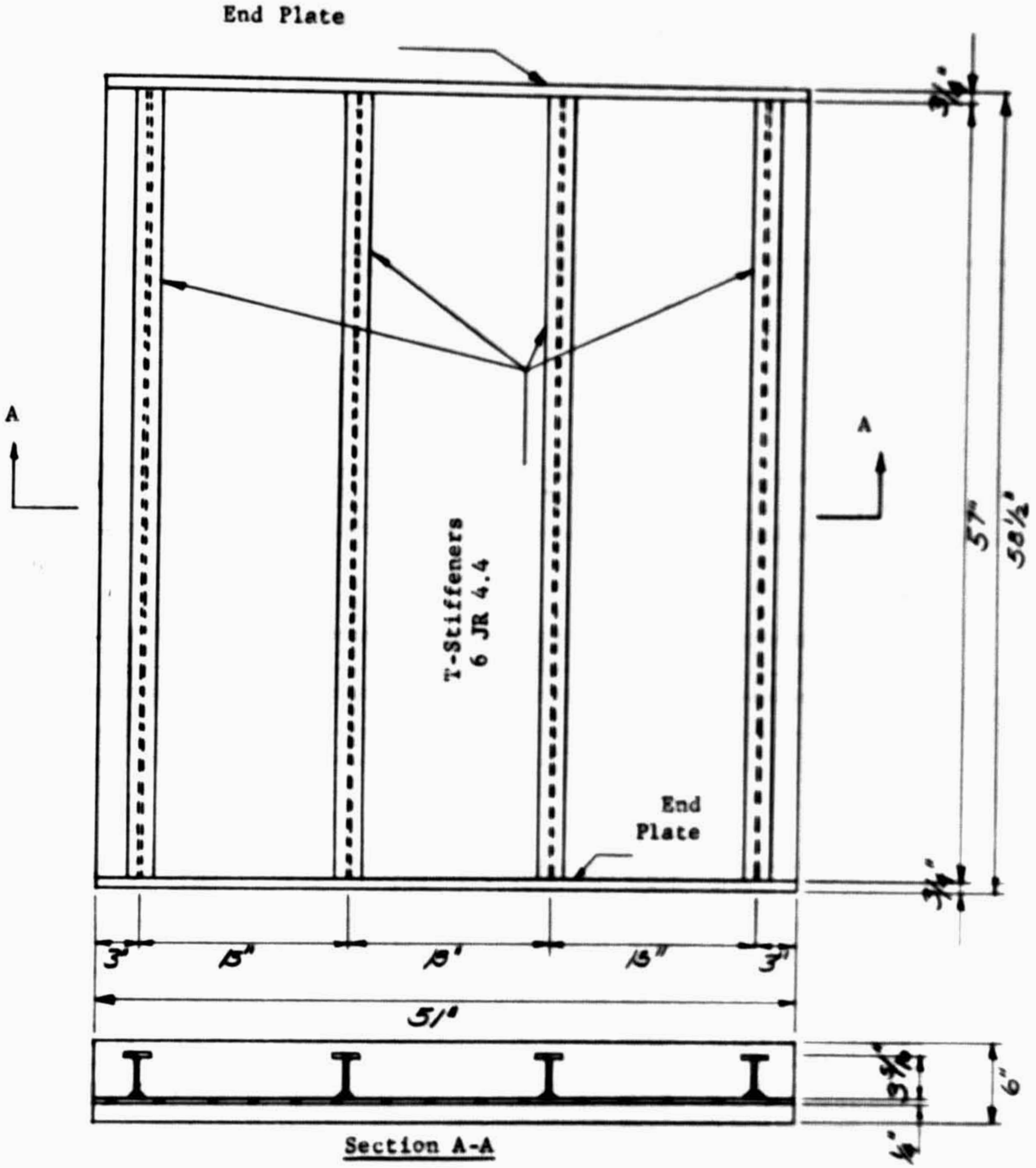
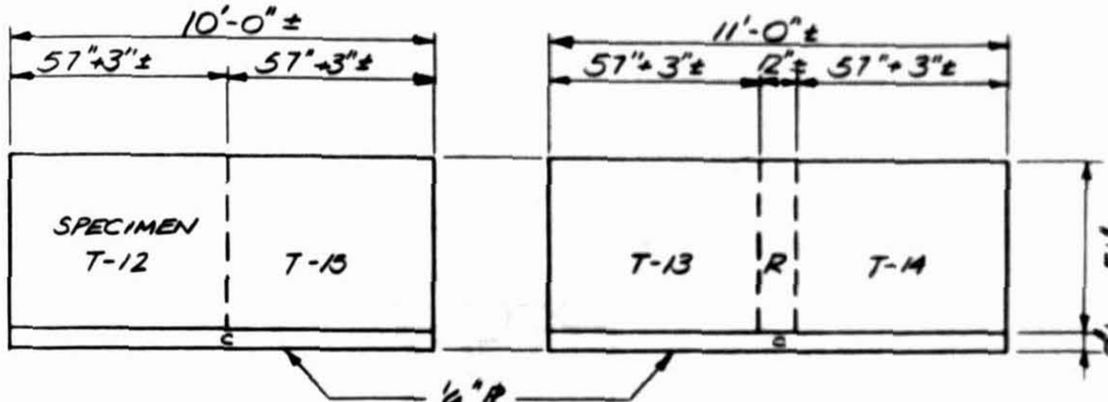


Fig. 1 - TEST SPECIMEN (T-12 T-15)
Scale: 1"=1'-0"



PLATES

STIFFENERS

Note:
- R: Reserved pieces for residual stress measurement
- C: Reserved pieces for coupon tests

Fig. 2-MATERIAL CUTTING DIAGRAMS
No Scale

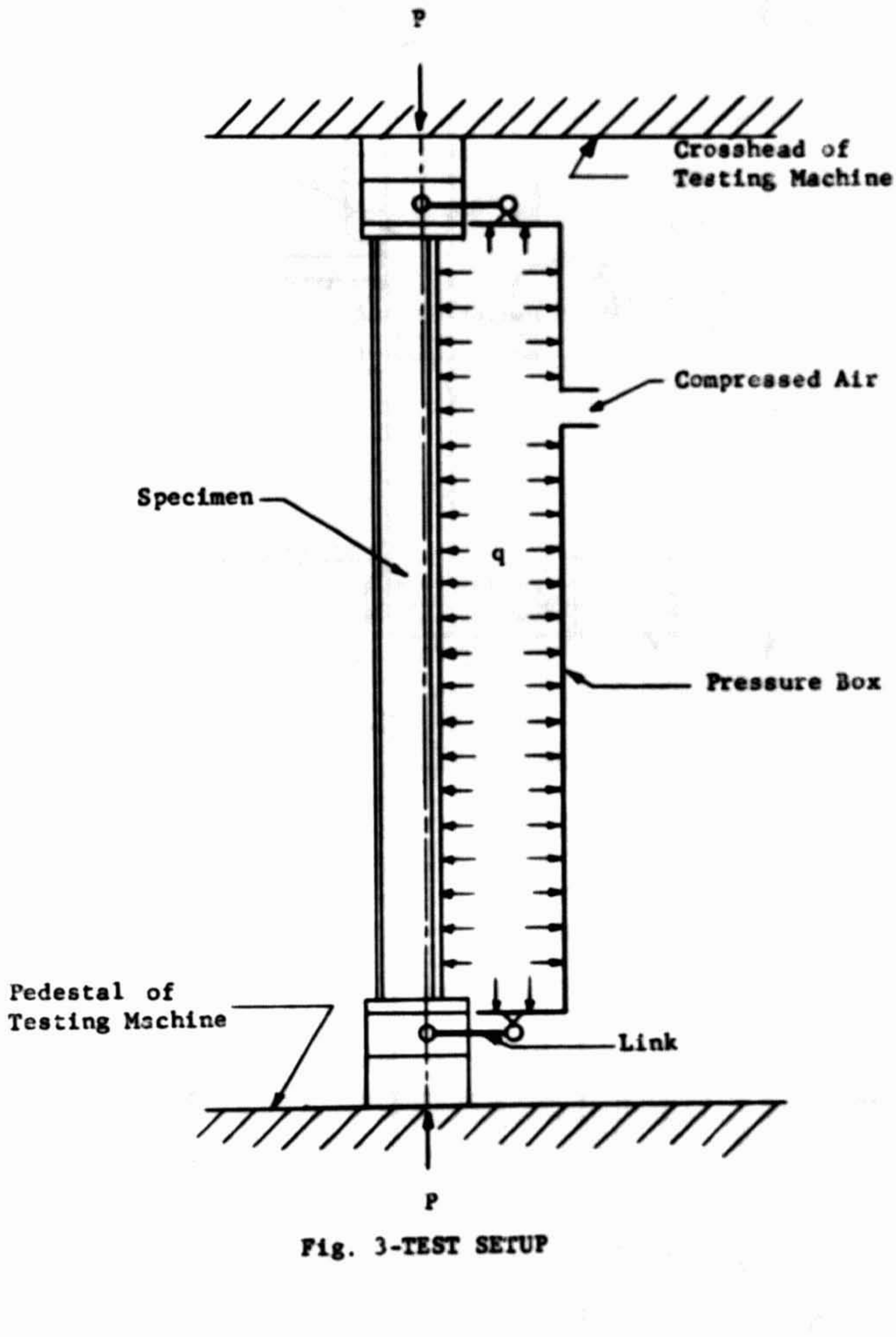


Fig. 3-TEST SETUP

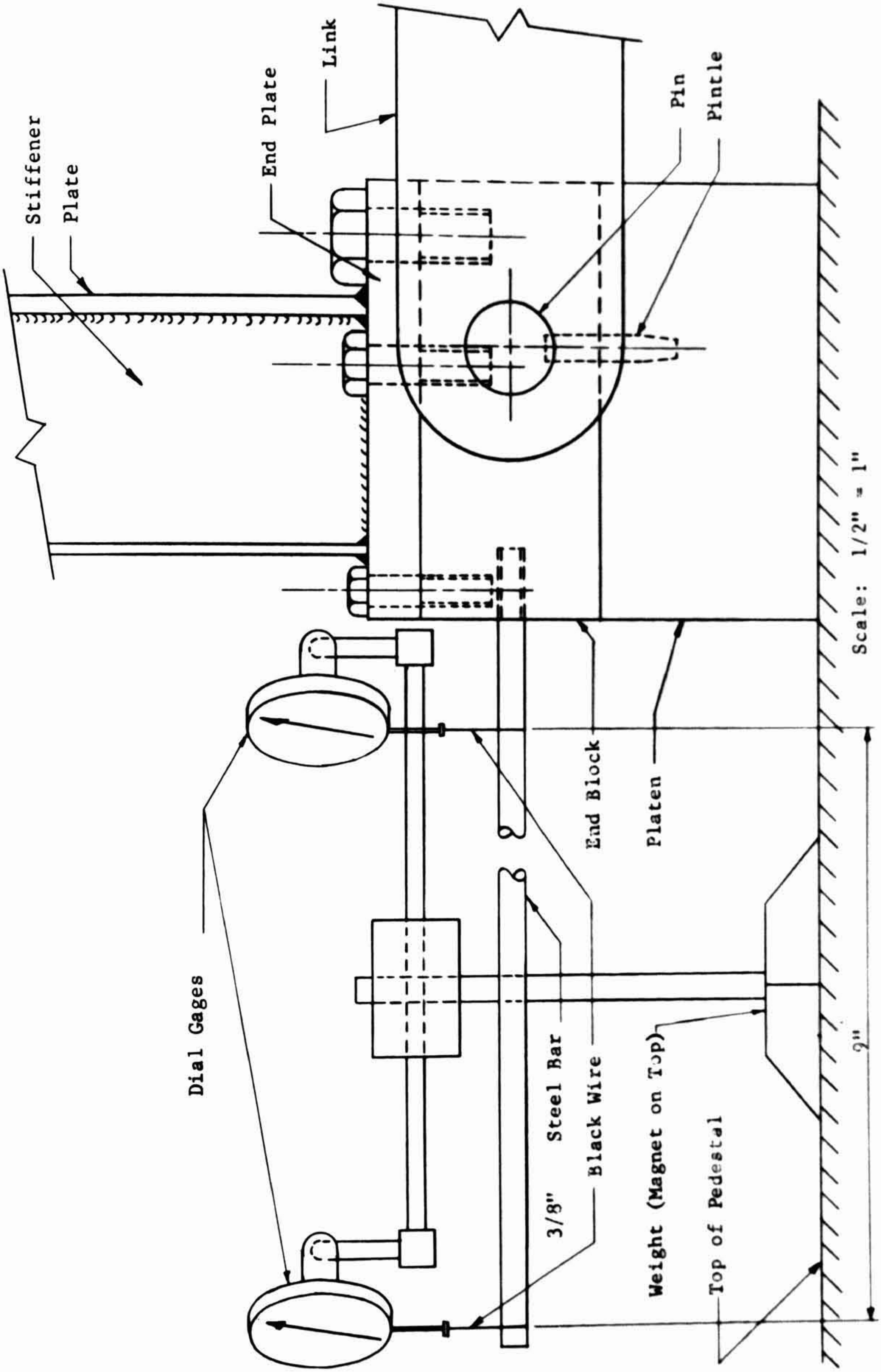


Fig. 4 - END FIXTURE AND ATTACHEMENT OF S-DIAL GAGES

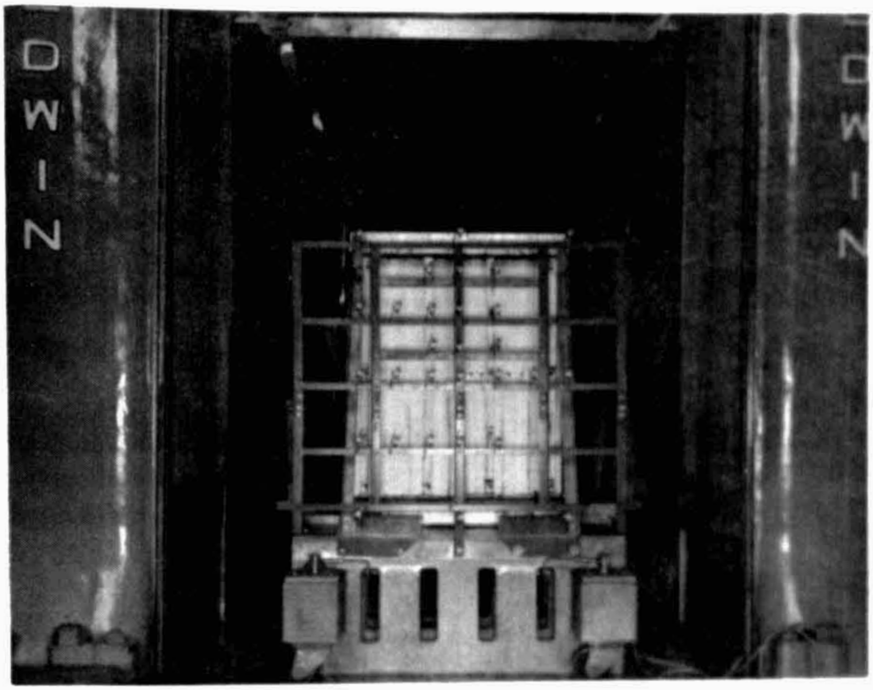
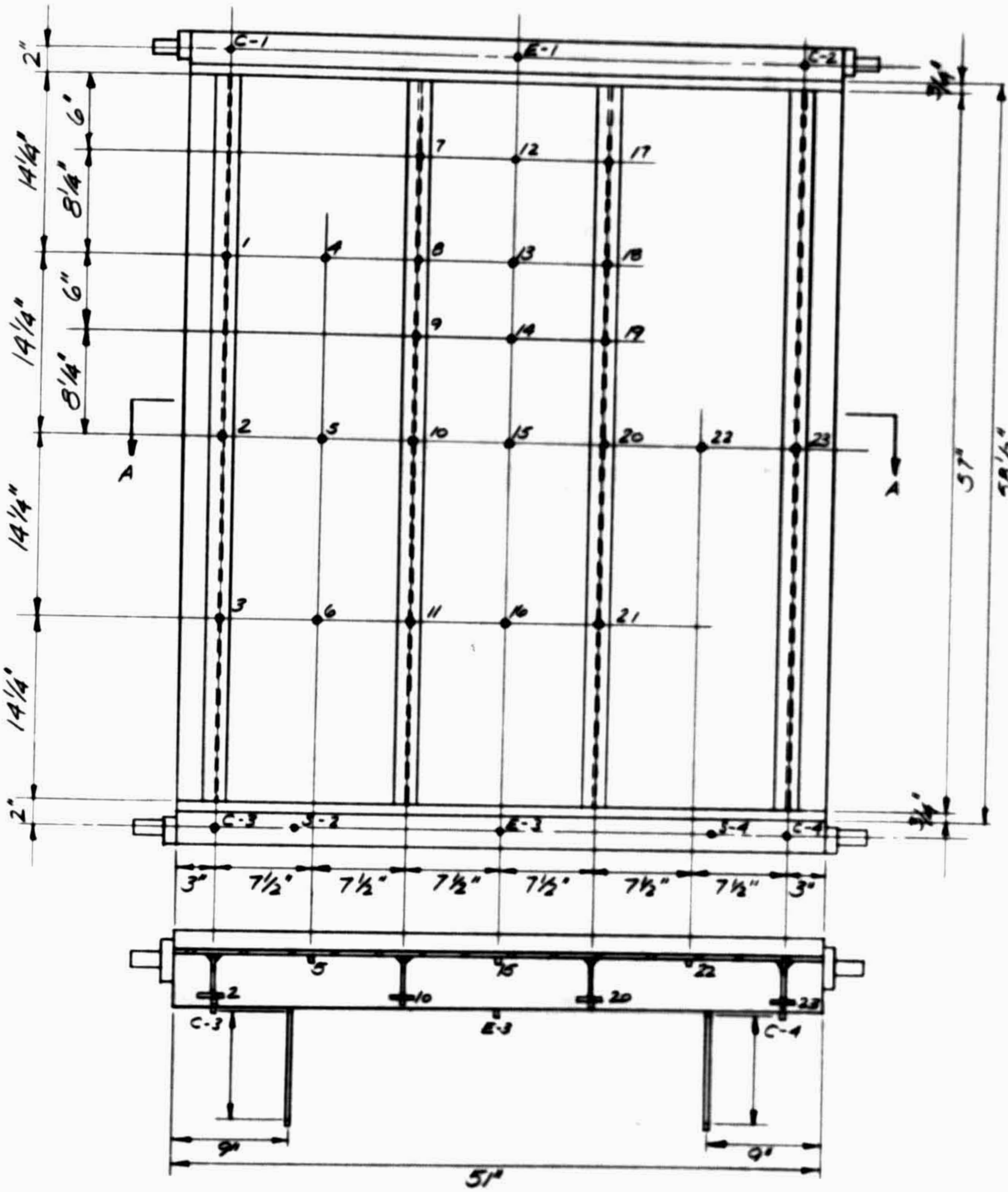
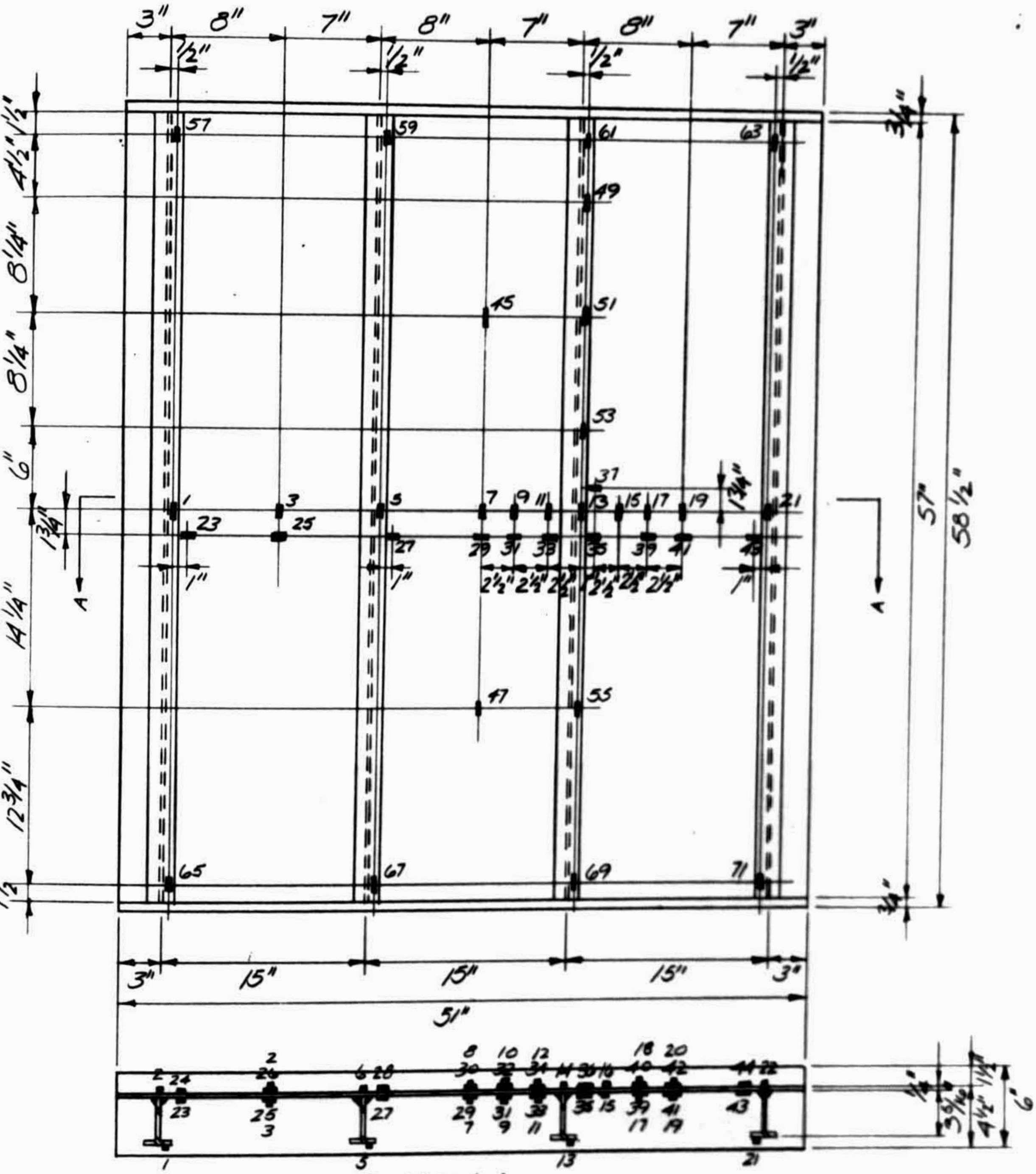


Fig. 5 SPECIMEN TEST ASSEMBLY
FRONT VIEW



Section A-A

Fig. 6 LOCATION OF DIAL GAGES
Scale: 1" = 1' - 0"



Section A-A

Fig. 7 LOCATION OF SR-4 STRAIN GAGES
Scale: 1" = 1' - 0"

Note: For each gage on the front face there is a corresponding gage on the back face. The gage number on the back face is the following even number to that of the gage on the front face.

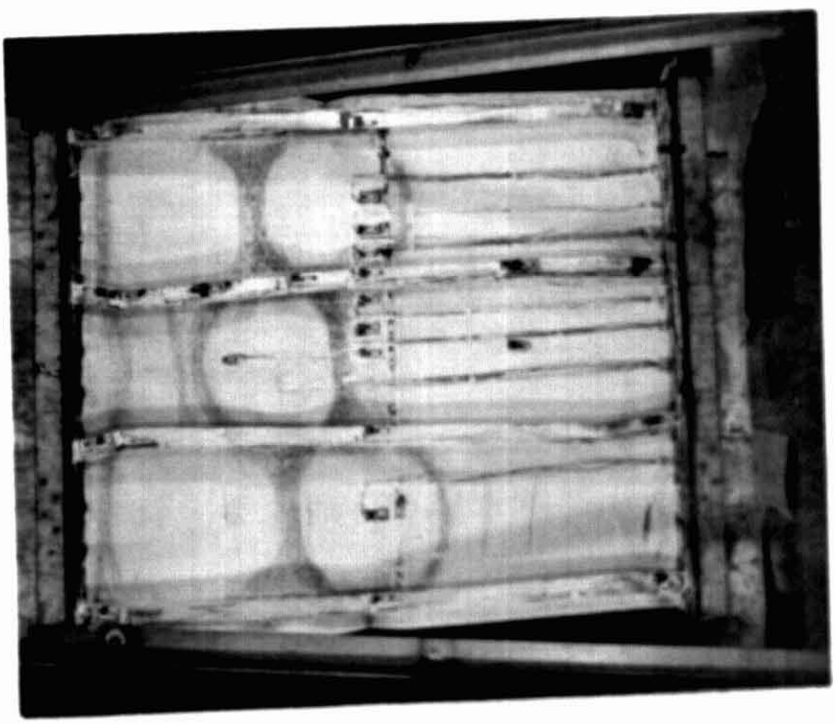


Fig. 8 SPECIMEN T12 AFTER TEST
FRONT FACE

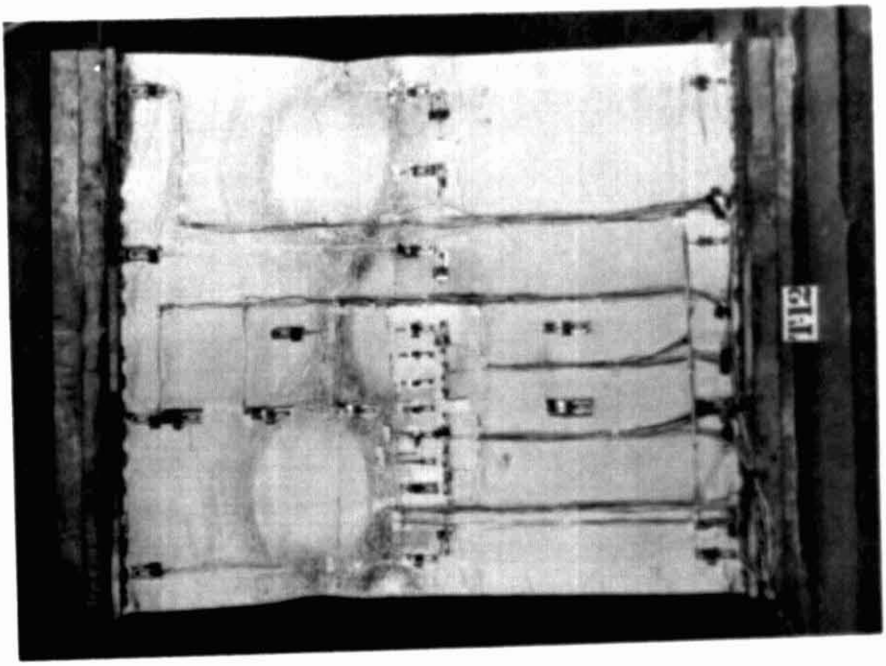


Fig. 9 SPECIMEN T12 AFTER TEST
BACK FACE

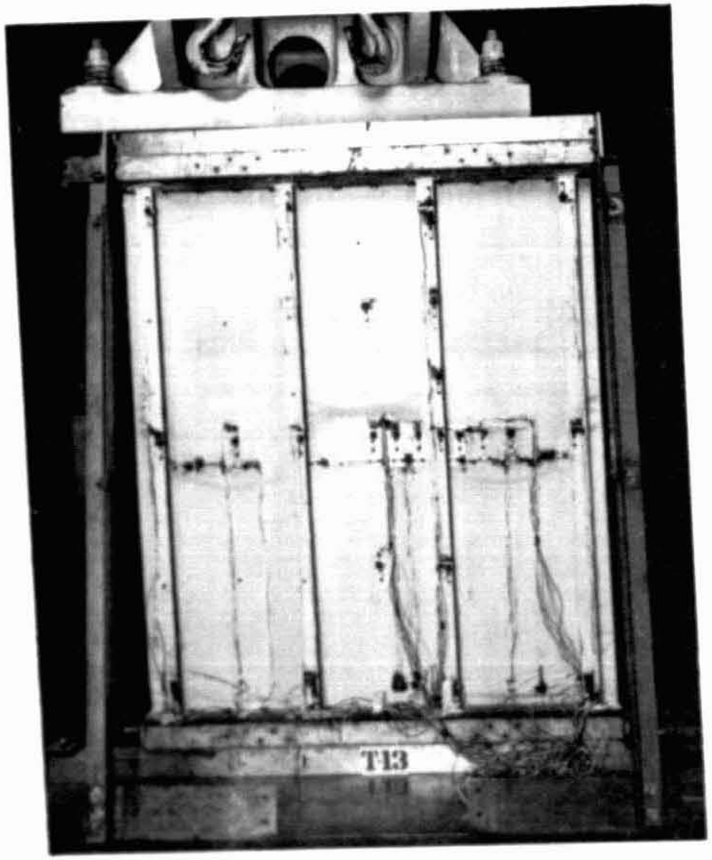


Fig. 10 SPECIMEN T13 AFTER TEST
FRONT FACE

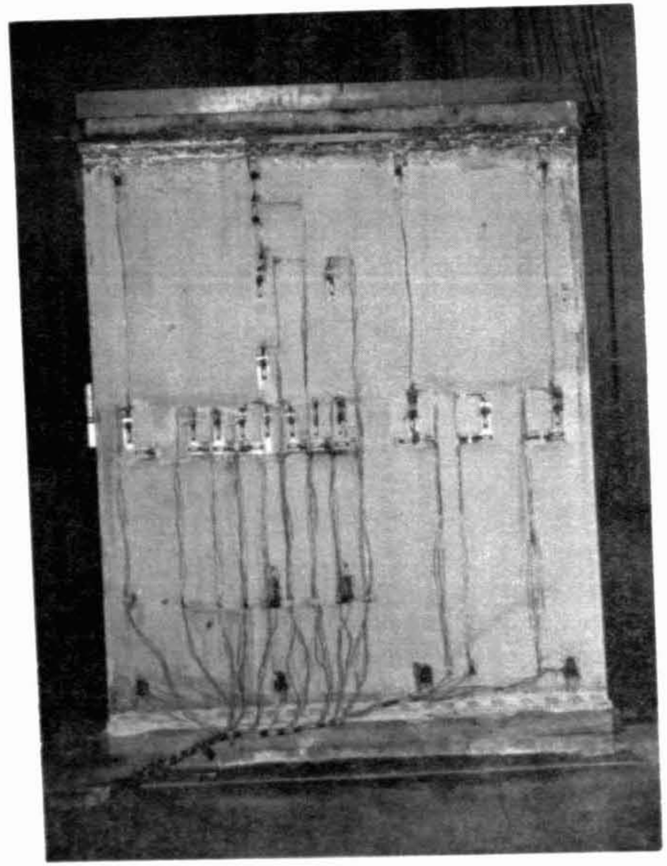


Fig. 11 SPECIMEN T13 AFTER TEST
BACK FACE

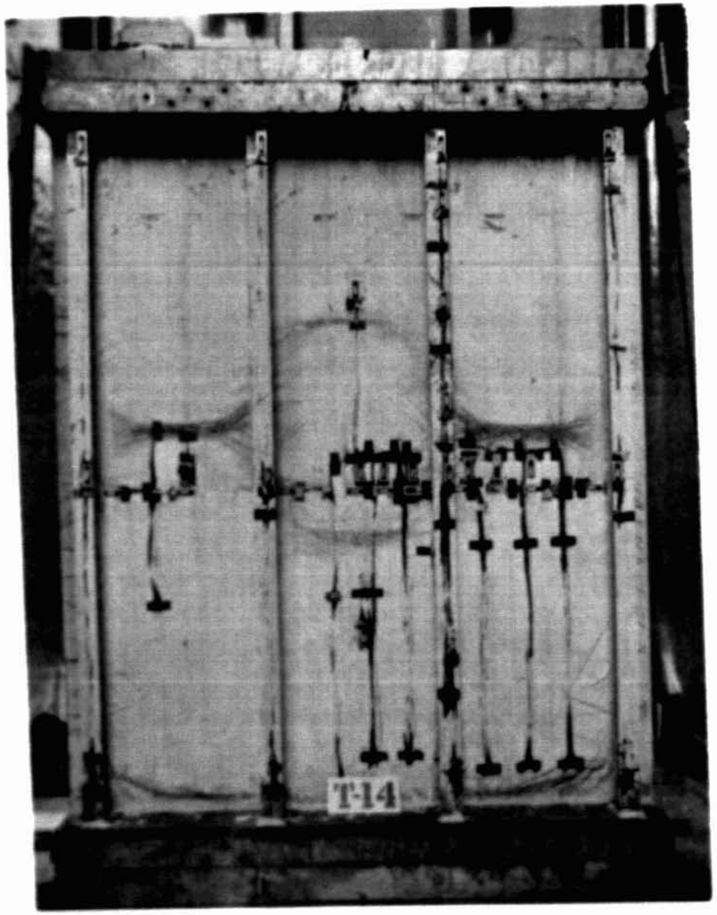


Fig 12 SPECIMEN T14 AFTER TEST
FRONT FACE

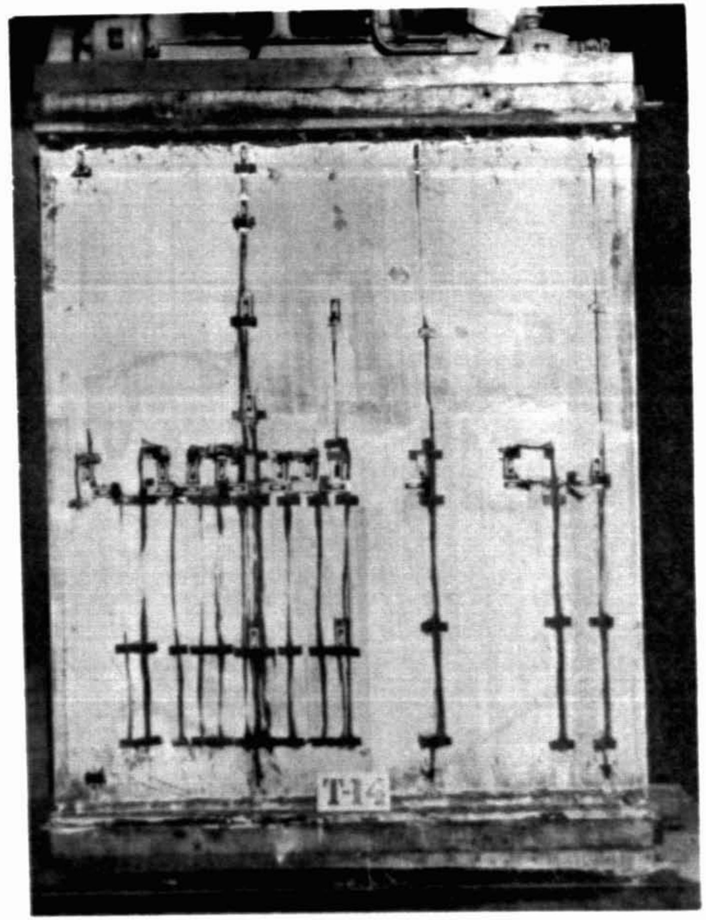


Fig. 13 SPECIMEN T14 AFTER TEST
BACK FACE

Fig. 14 SPECIMEN T15 AFTER TEST
FRONT FACE

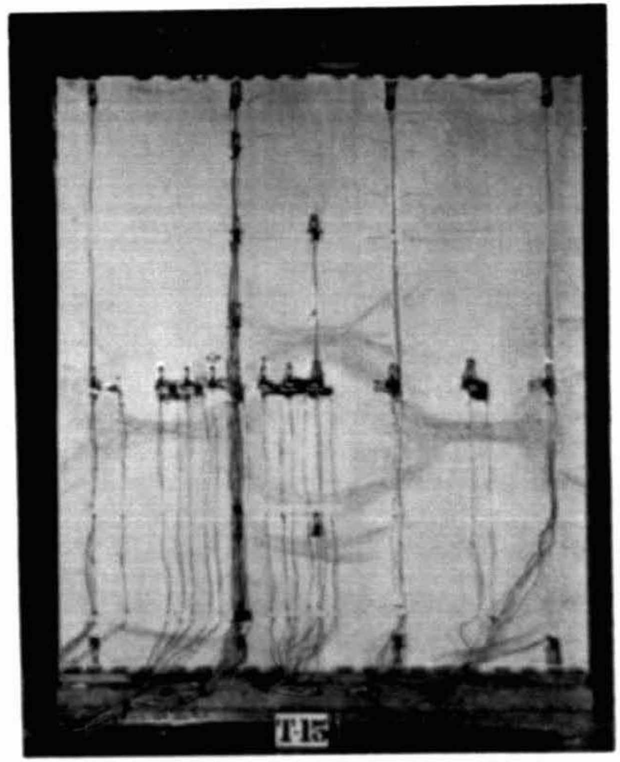


Fig. 15 SPECIMEN T15 AFTER TEST
BACK FACE

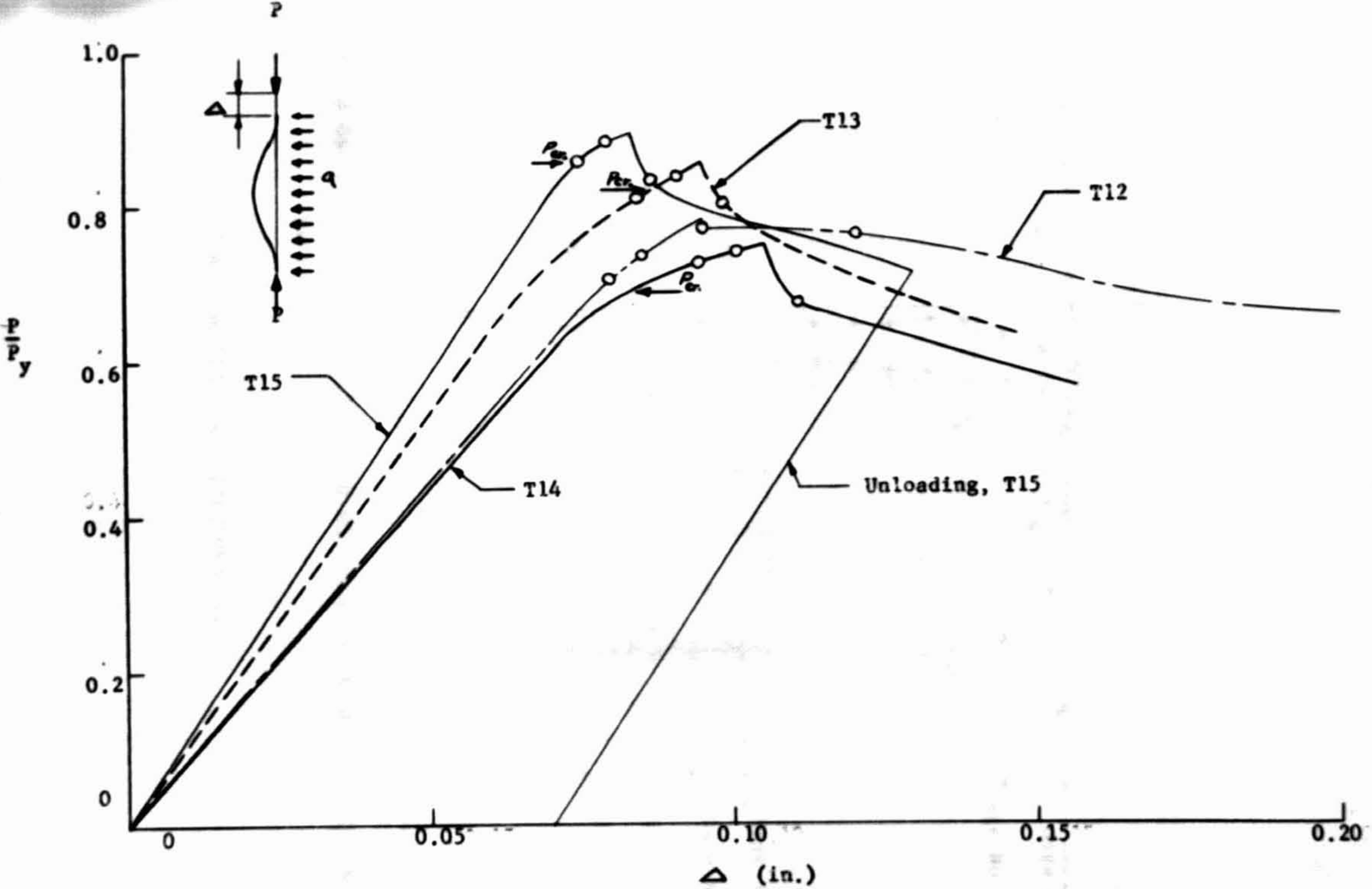


Fig. 16 - LONGITUDINAL DEFLECTION SPECIMENS T12 TO T15.

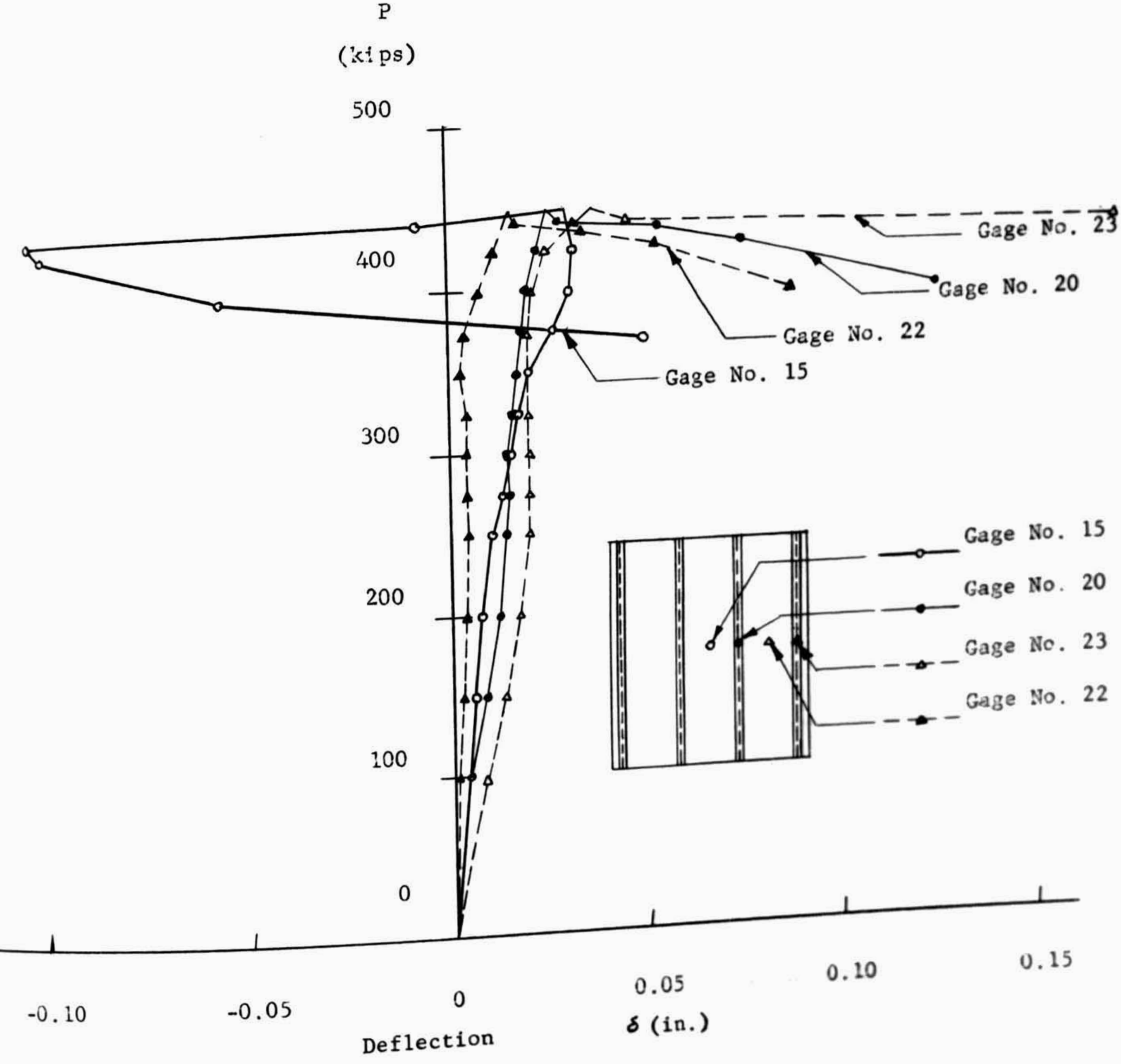


Fig. 17 LATERAL DEFLECTION, SPECIMEN T12

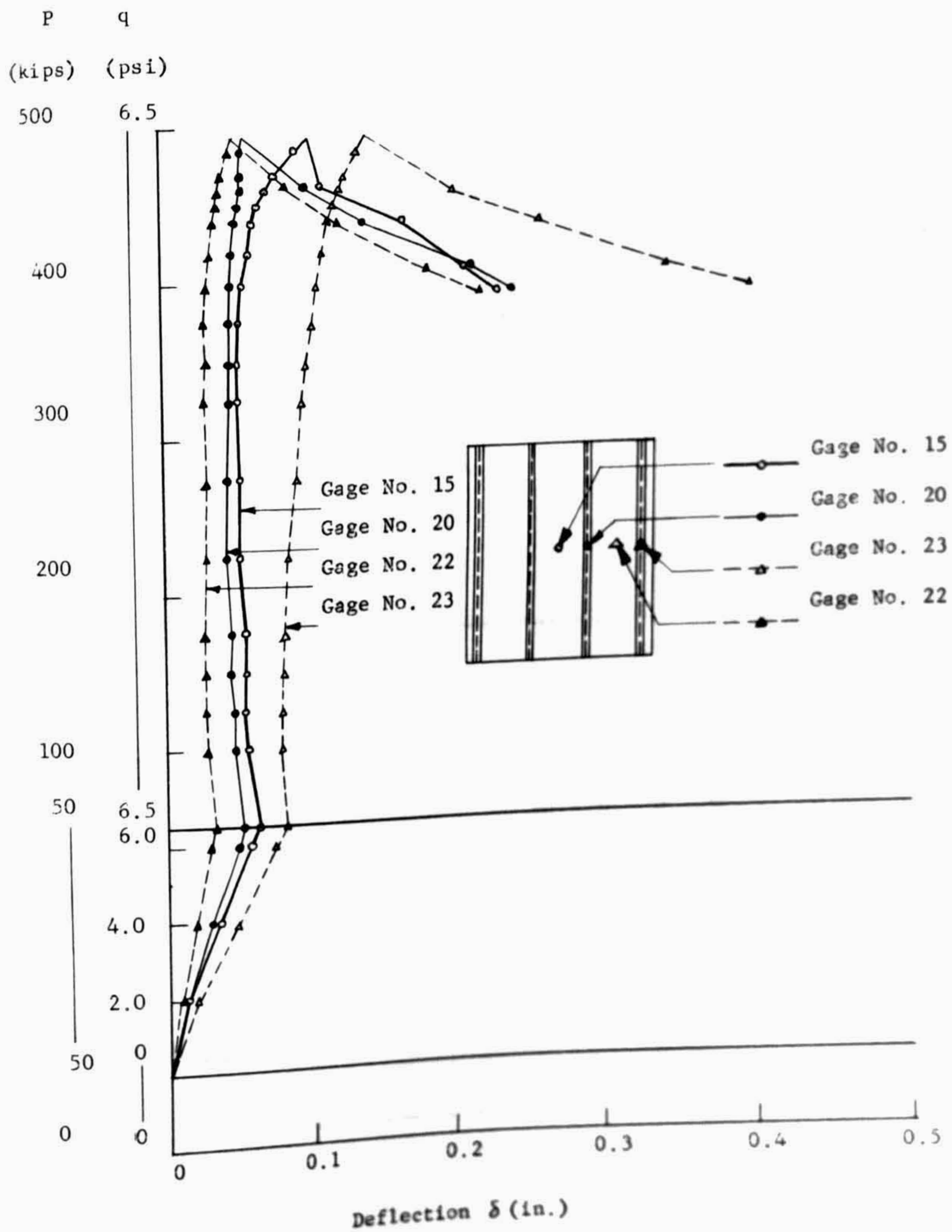


Fig. 18 LATERAL DEFLECTION, SPECIMEN T 13

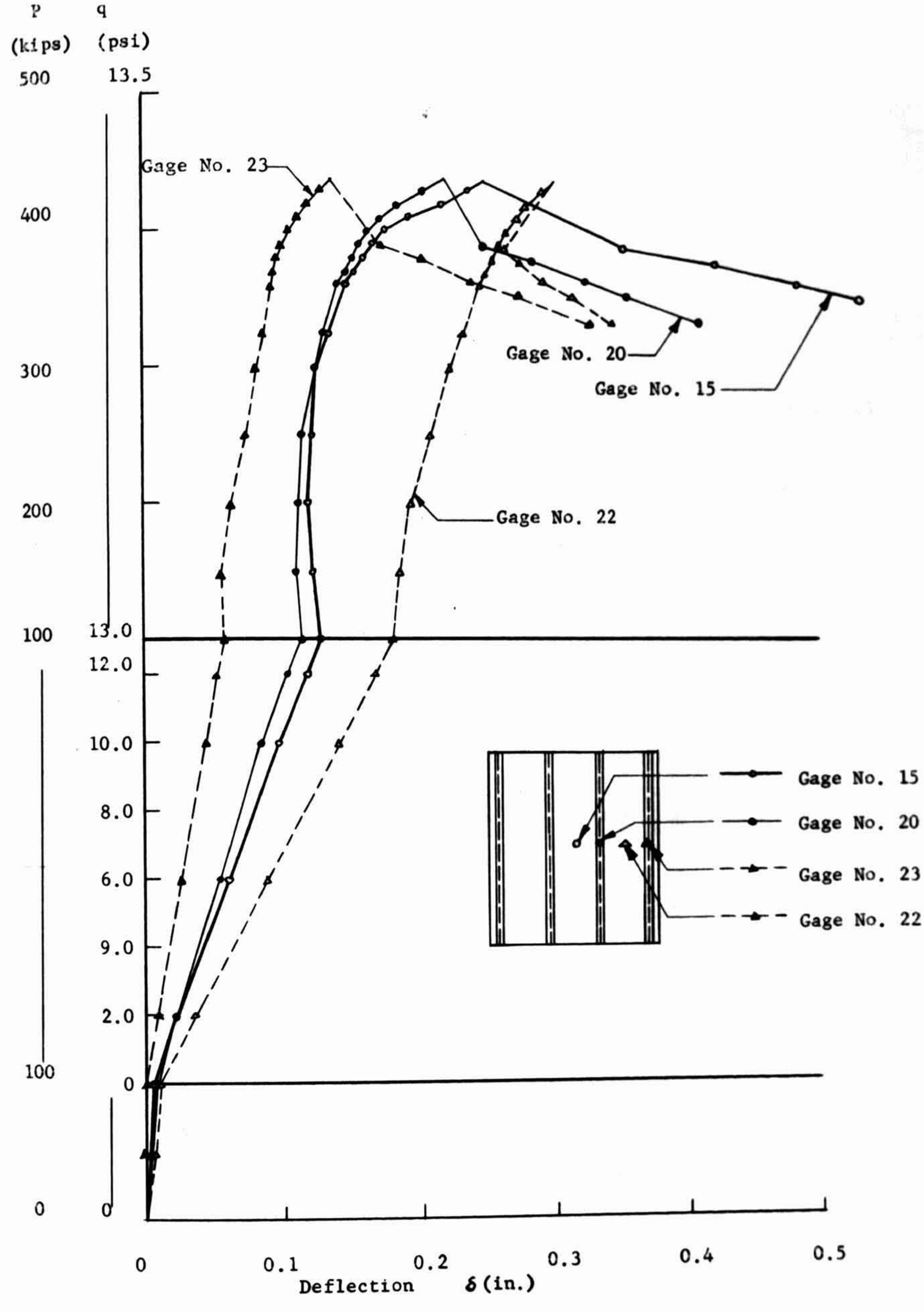


Fig. 19 LATERAL DEFLECTION, SPECIMEN T 14

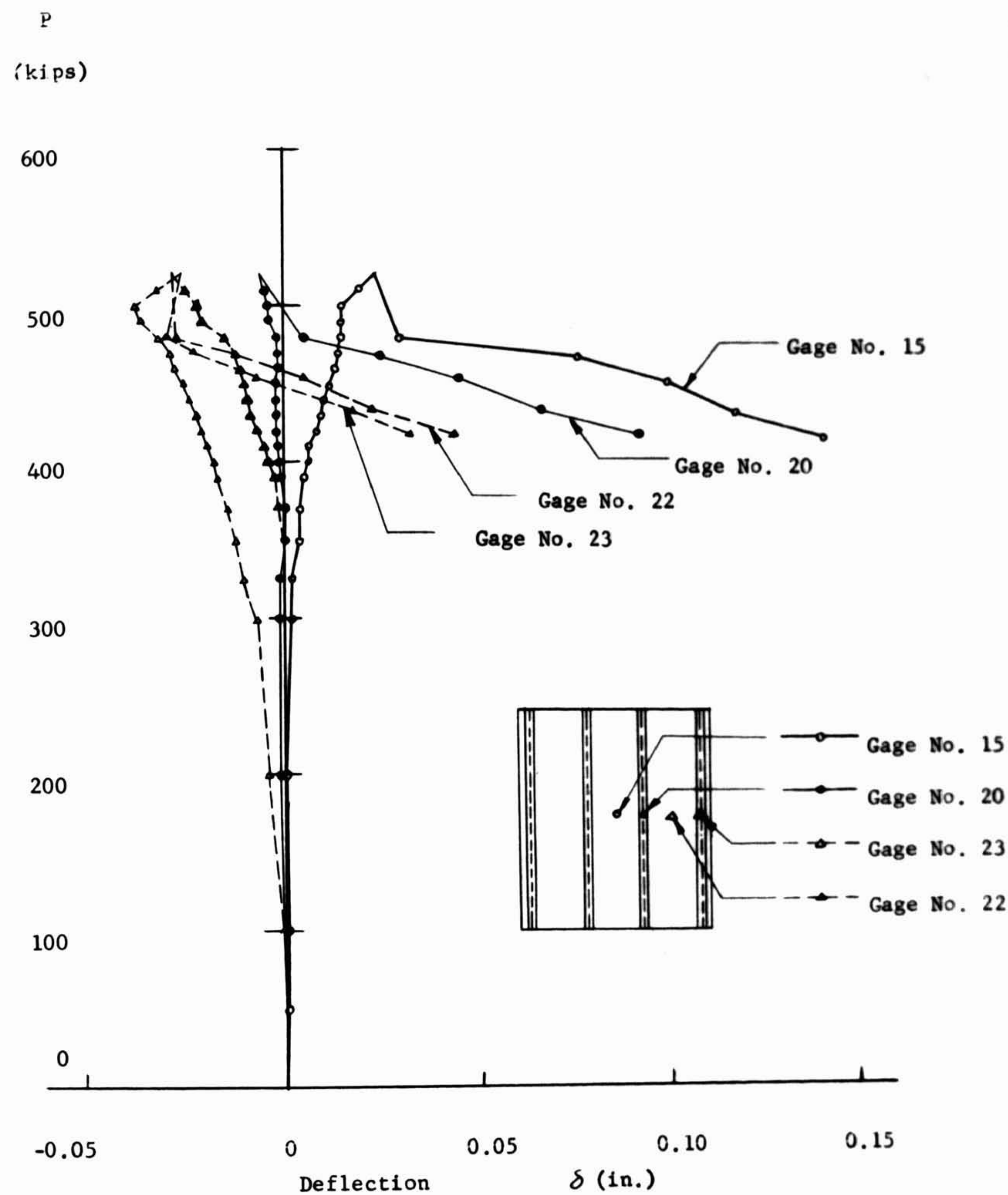


Fig. 20 LATERAL DEFLECTION, SPECIMEN T15

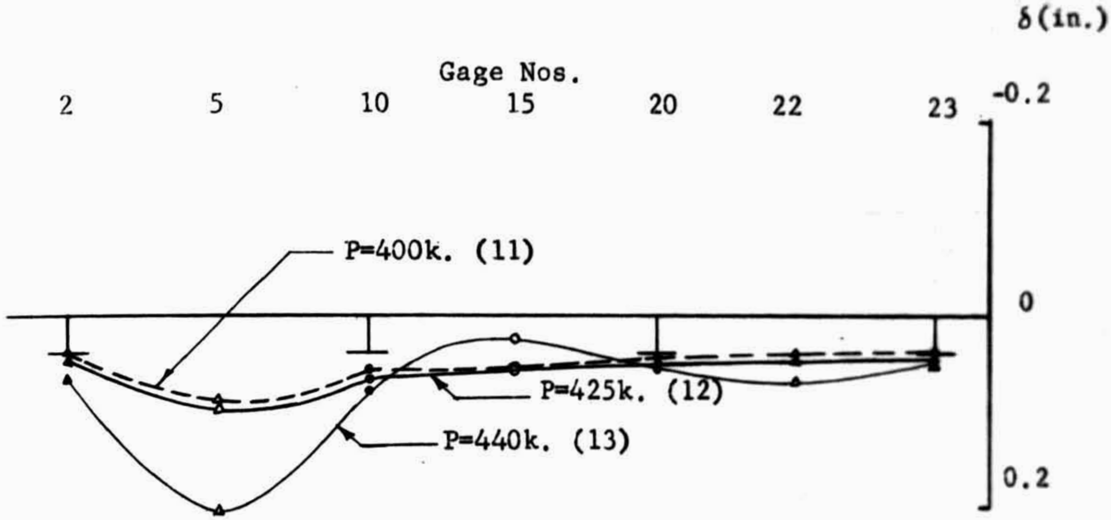


Fig. 21 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T12

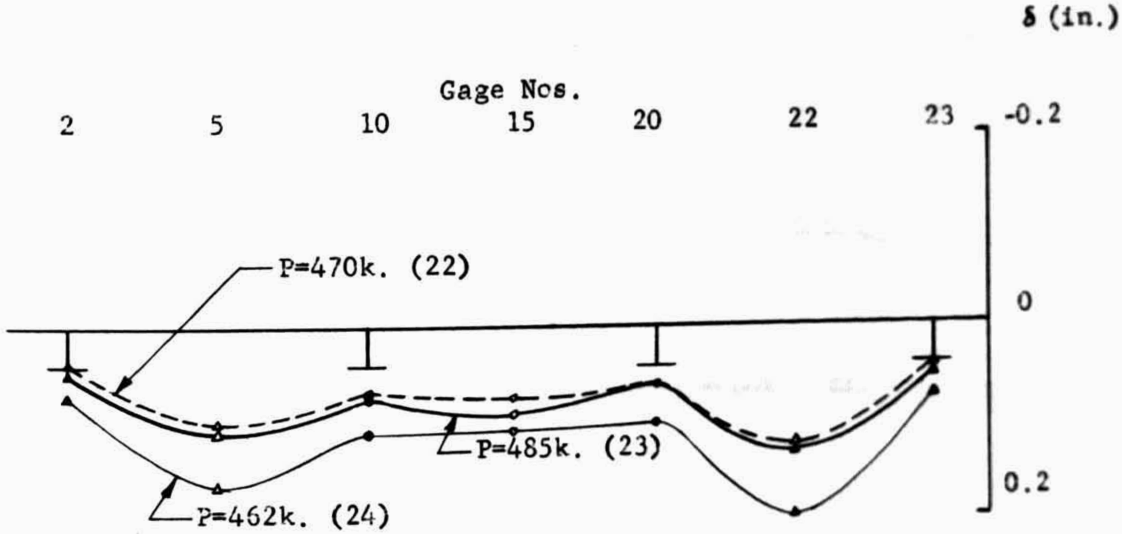


Fig. 22 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T13

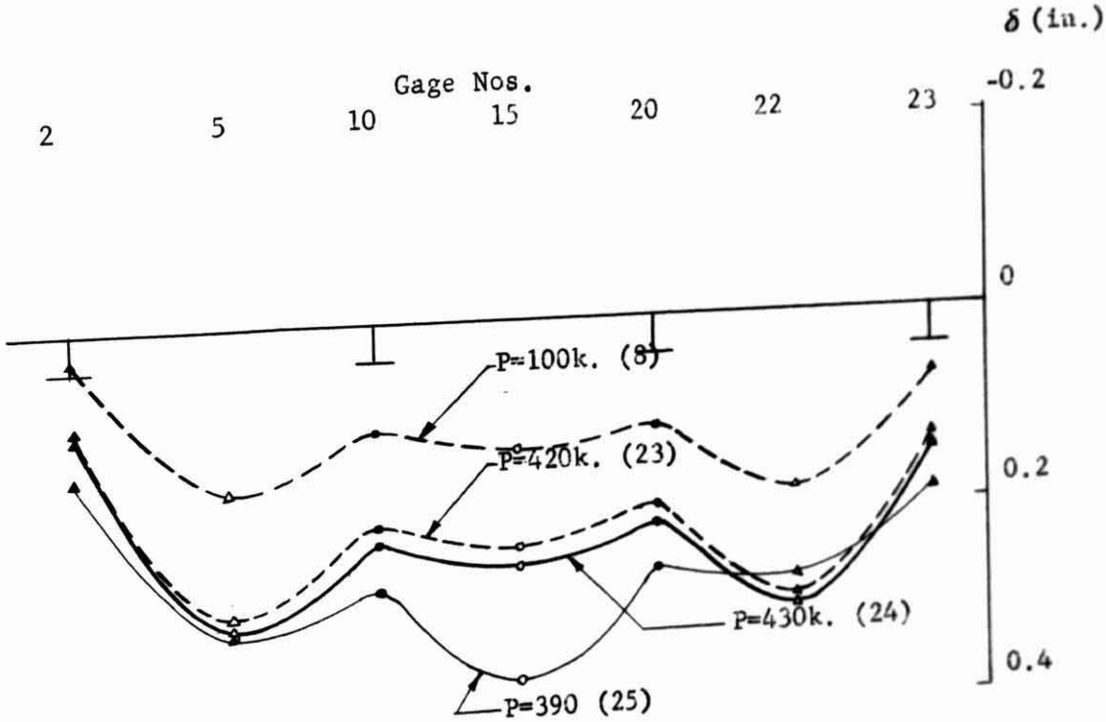


Fig. 23 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T14

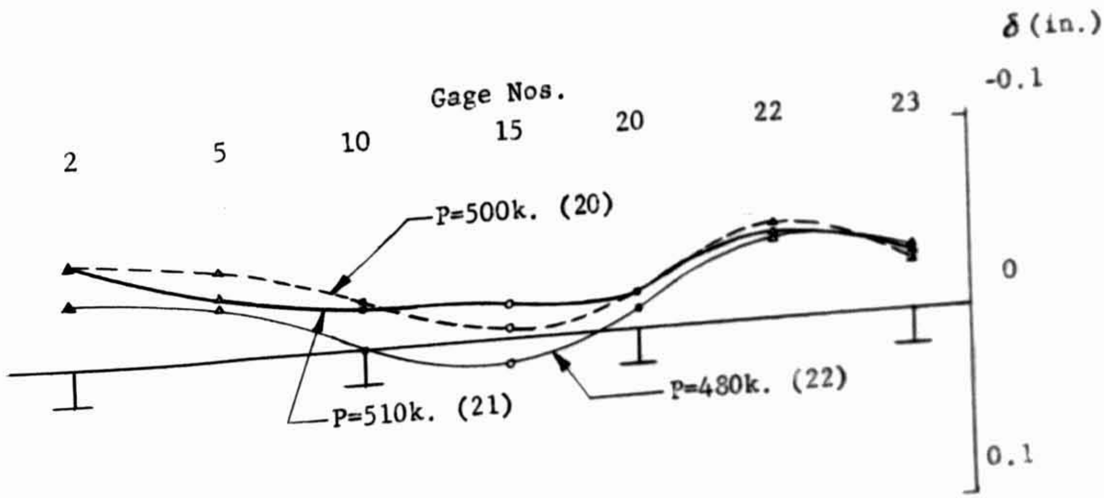


Fig. 24 DEFORMATION OF MID-HEIGHT CROSS SECTION, SPECIMEN T15

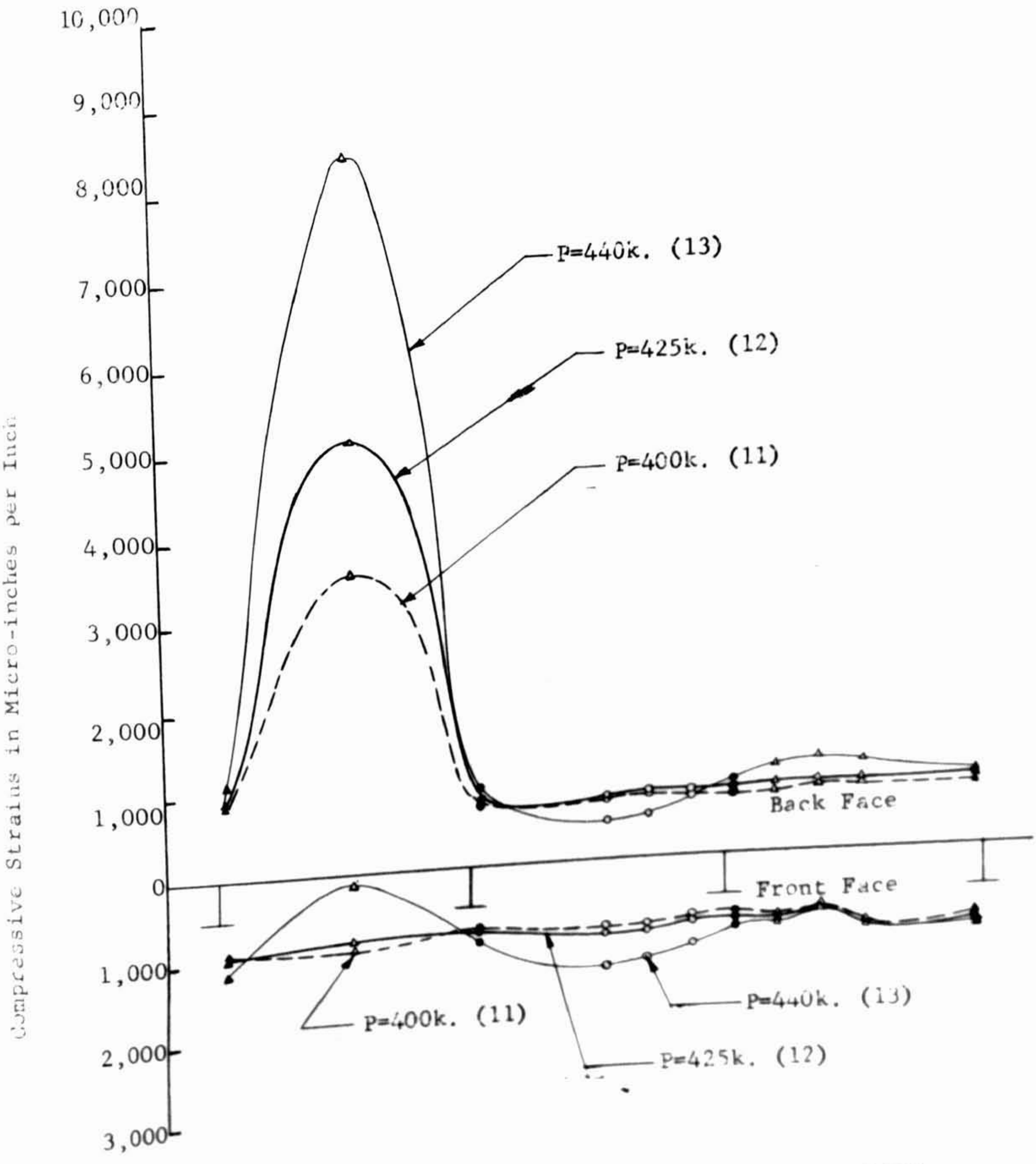


Fig. 25 AXIAL STRAINS IN PLATE OF SPECIMEN T12, MID-HEIGHT

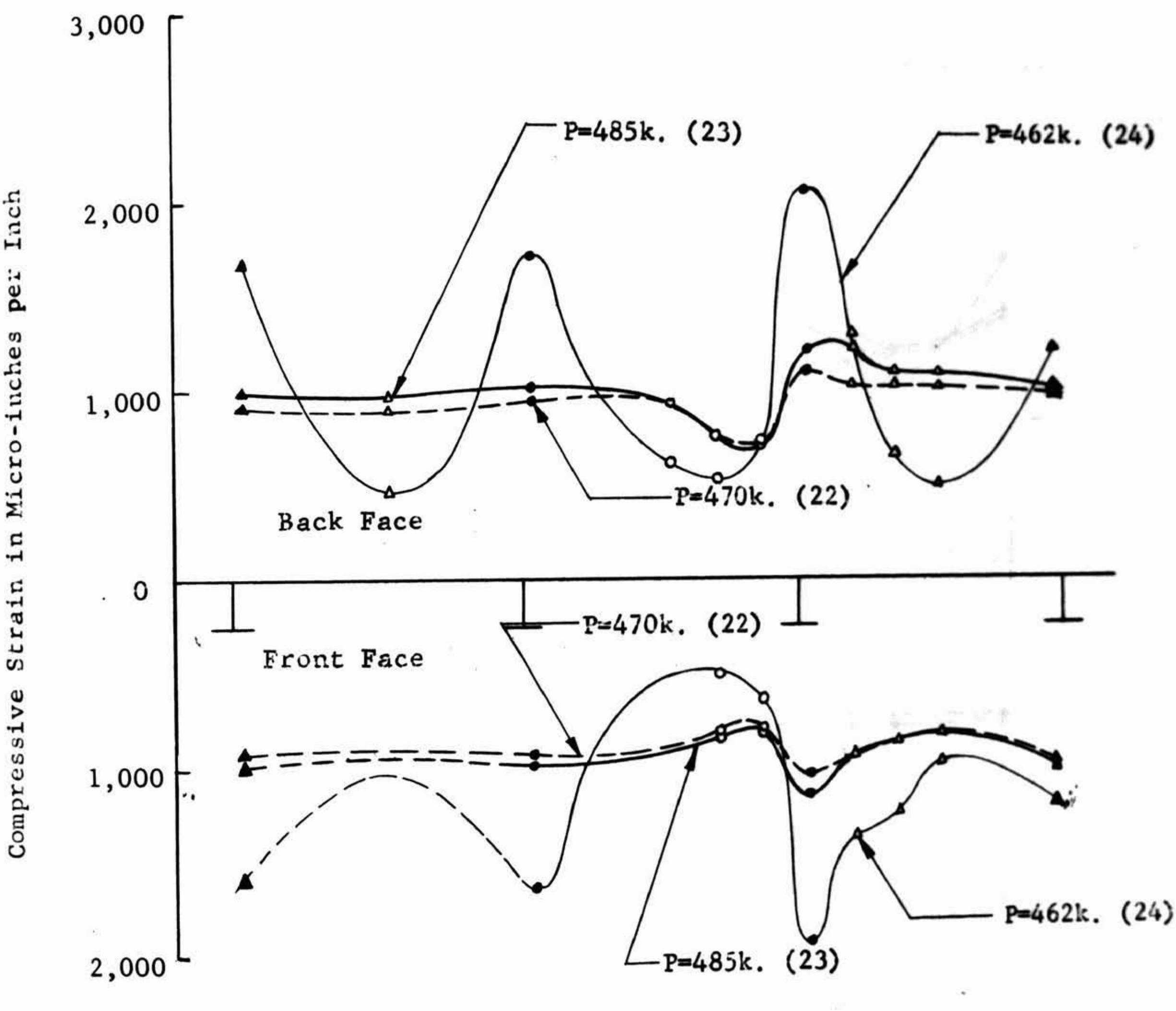


Fig. 26 AXIAL STRAINS IN PLATE OF SPECIMEN T13, MID-HEIGHT

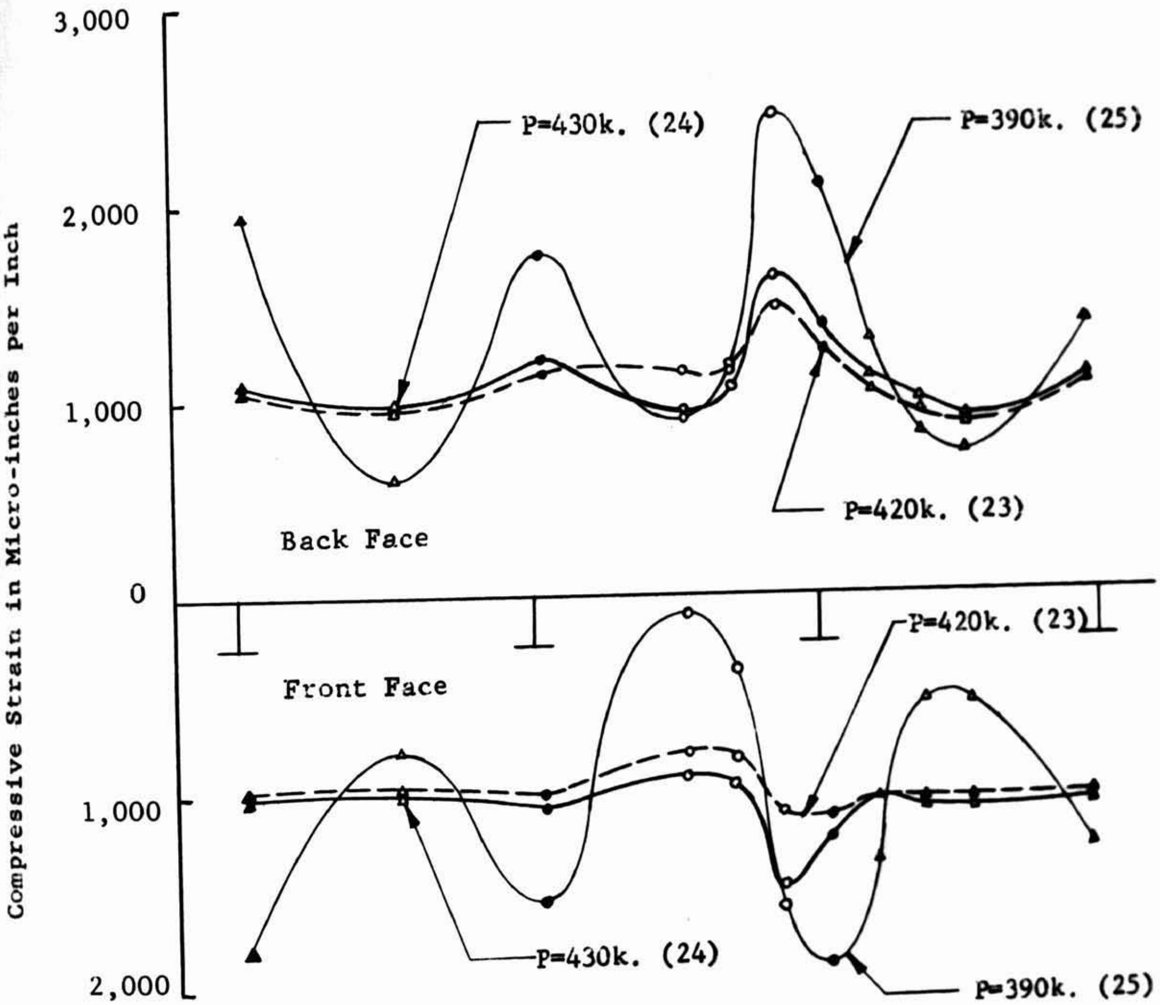


Fig. 27 AXIAL STRAINS IN PLATE OF SPECIMEN T14, MID-HEIGHT

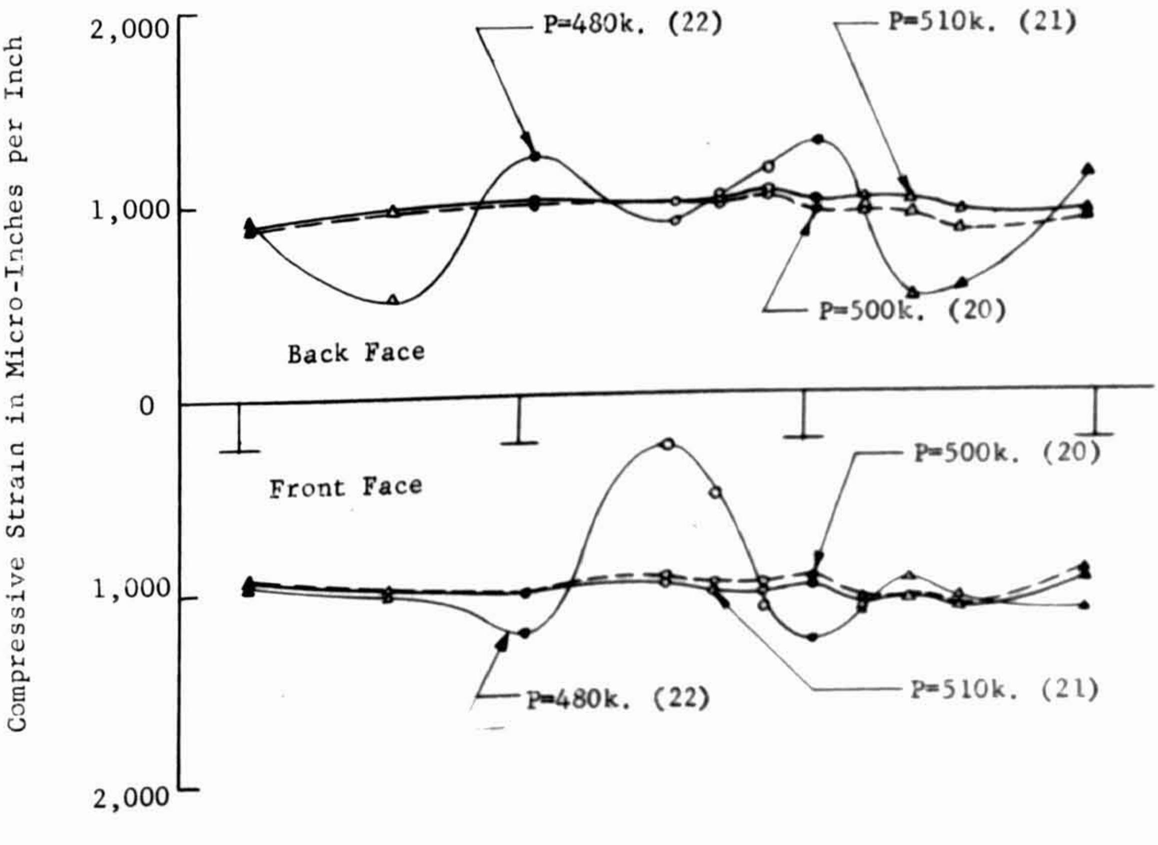


Fig. 28 AXIAL STRAINS IN PLATE OF SPECIMEN T15, MID-HEIGHT

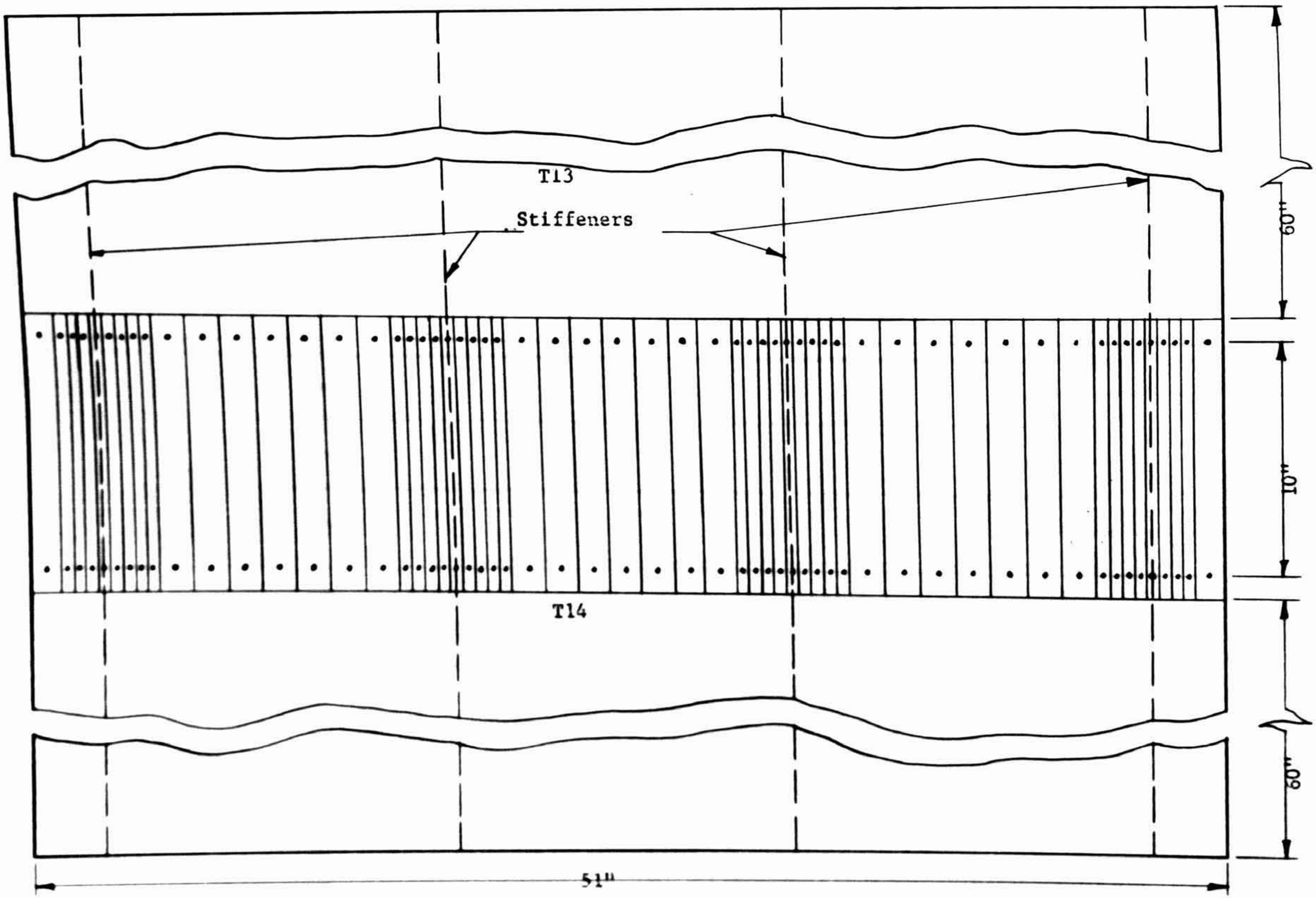


Fig. 29 LOCATION OF GAGE HOLES FOR RESIDUAL STRESS MEASUREMENT IN PLATE

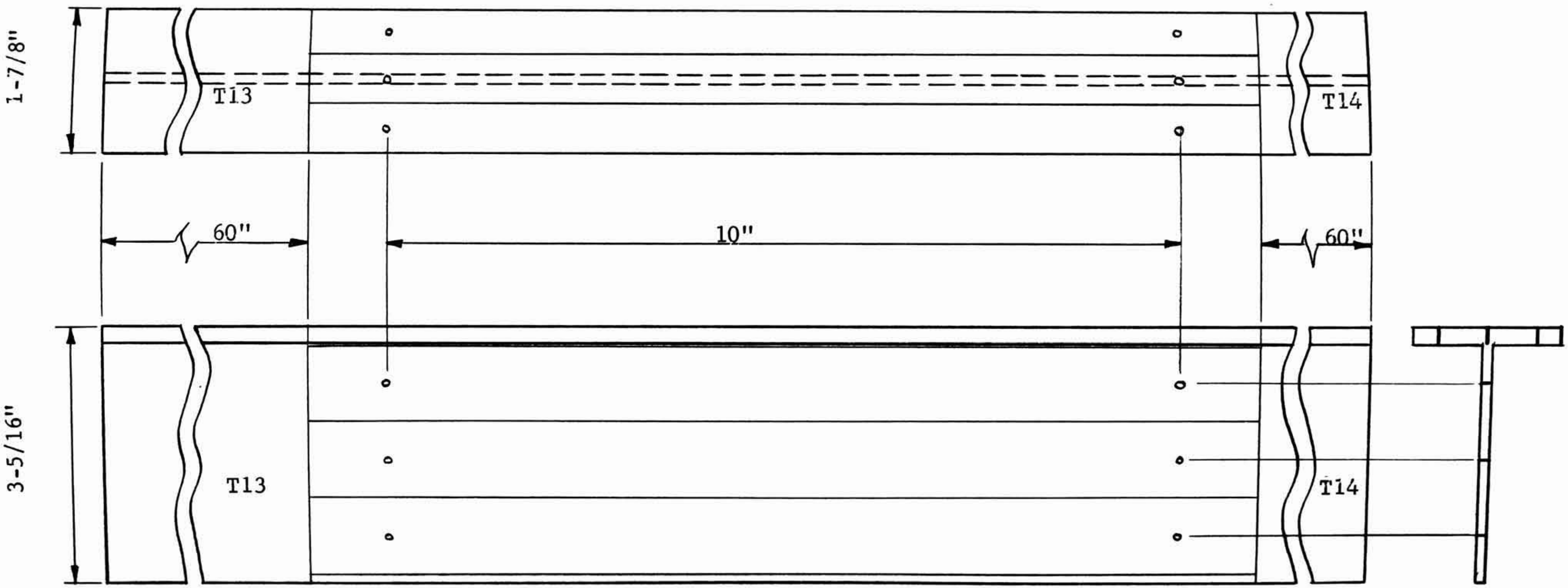


Fig. 30 LOCATION OF GAGE HOLE FOR RESIDUAL STRESS MEASUREMENT IN TEE STIFFENERS

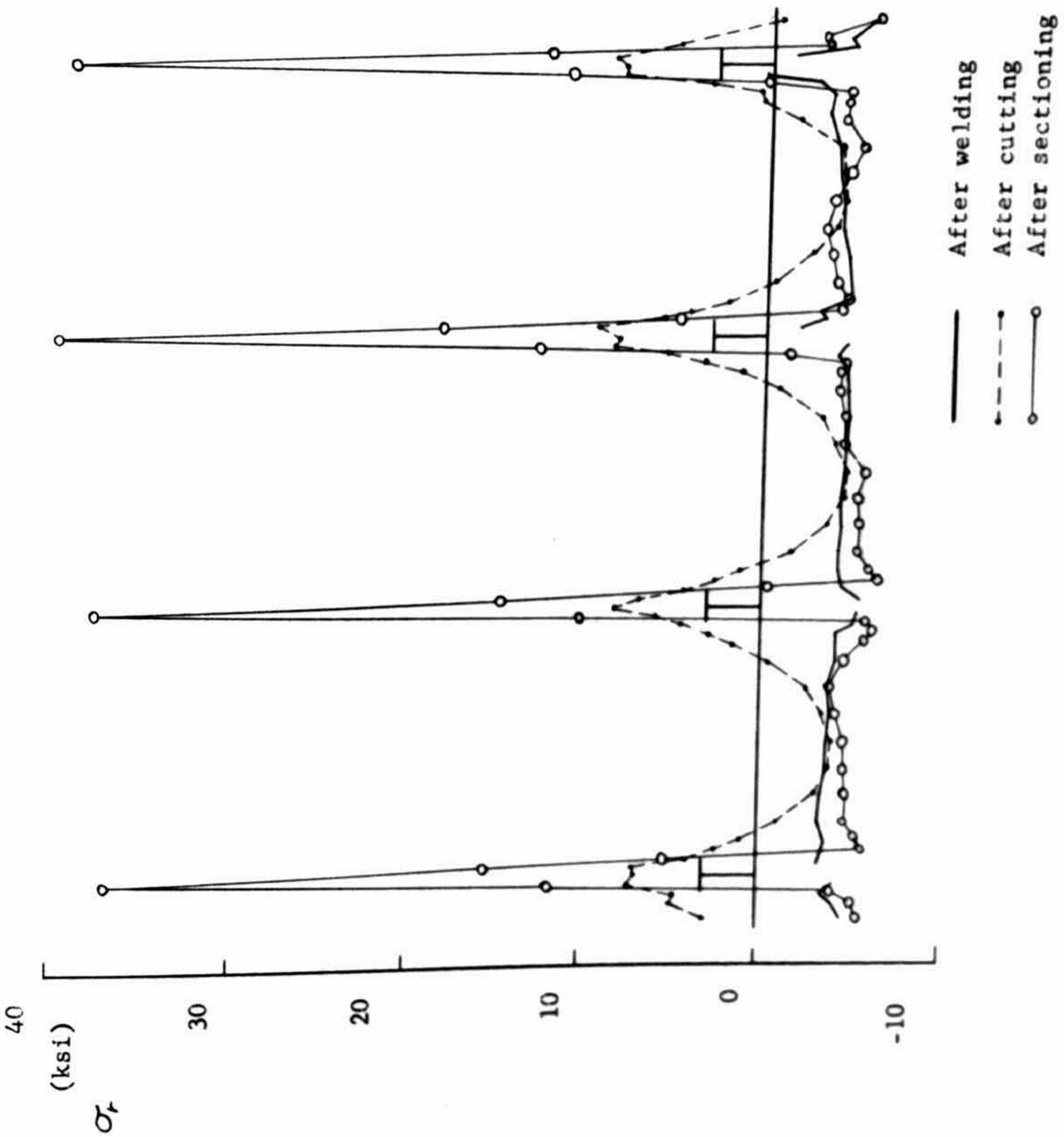


Fig. 31 - RESIDUAL STRESSES IN PLATE

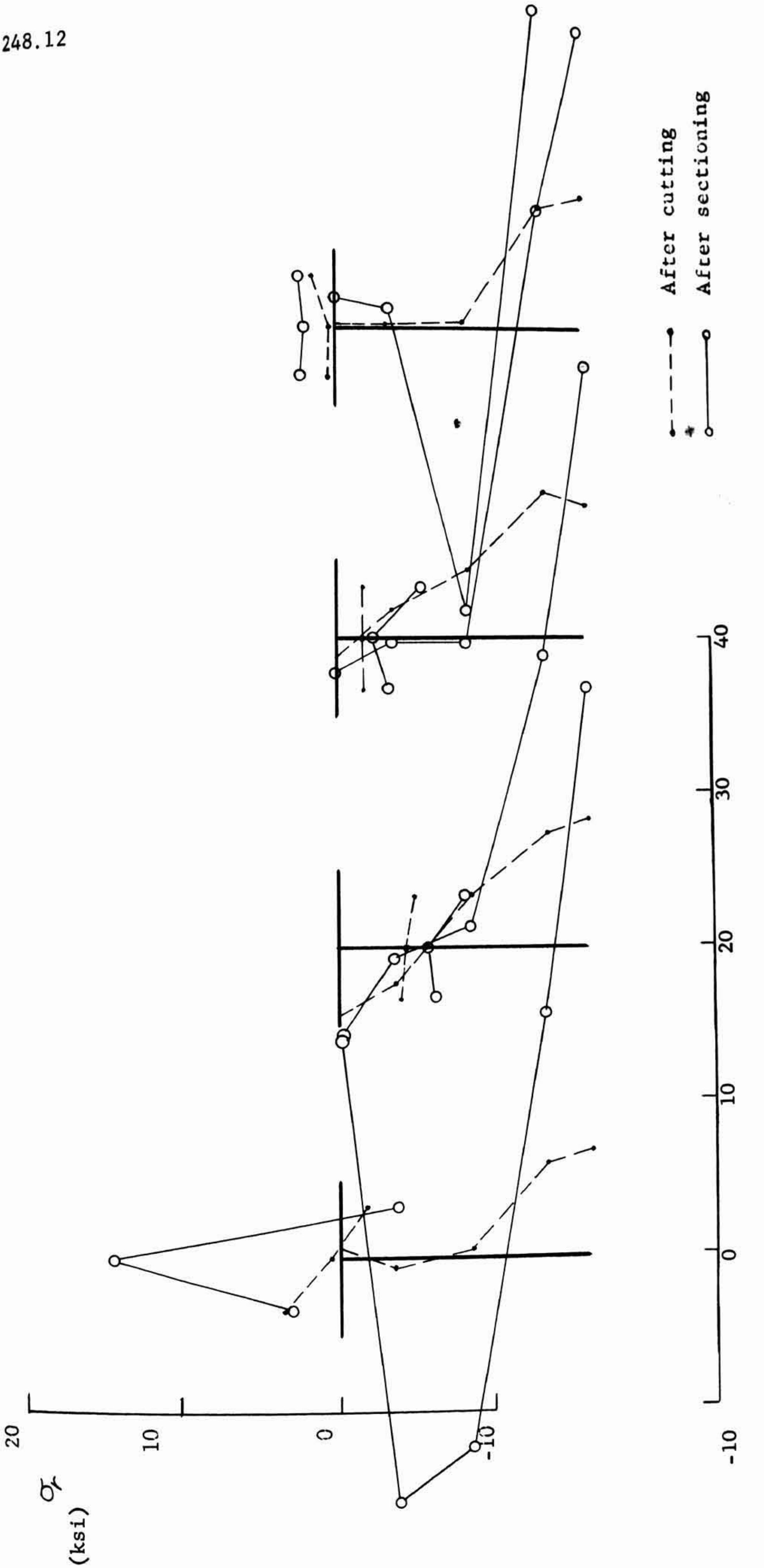


Fig. 32-RESIDUAL STRESSES IN TEE STIFFNERS

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